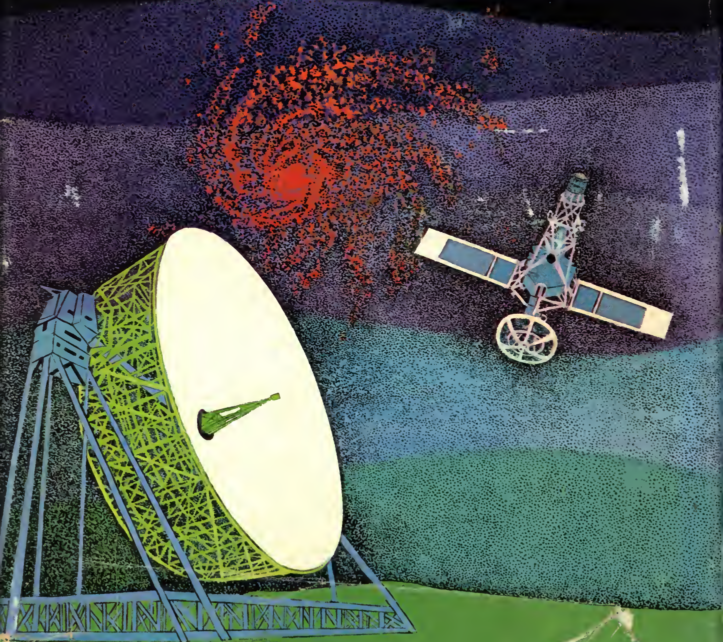
Colin A. Ronan

MAN PROBES THE UNIVERSE

The Story of Astronomy



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MAN PROBES THE UNIVERSE

COLIN A. RONAN

Astronomy is the oldest of the sciences. It is also the most modern.

The identification of galaxies, the theory of the expanding universe, the photographic reconnaissance of the moon's hidden side, conflicting theories of the origins of the universe—all these have made news in our own century.

Beginning with the dimensions of the solar system, which are understandable in terms of terrestrial distances and measurable in light-hours, this book gradually builds up a conception of the staggering distance involved with stars, galaxies, and galactic clusters. It explains how astronomers, by analysing the radiation that reaches us from these remote heavenly bodies, can discover what elements they are made of and what atomic processes are responsible for their vast outpourings of energy. Against this background are presented the facts and theories on which we base our understanding of the universe.

Colin A. Ronan is the Director of the Historical Section of the British Astronomical Association, a Fellow of the Royal Astronomical Society, and a Member of the Junior Astronomical Society.

He has written magazine articles and several books on astronomy and other fields of science.

Mr. Ronan has also conducted many radio and television programs for children and schools.

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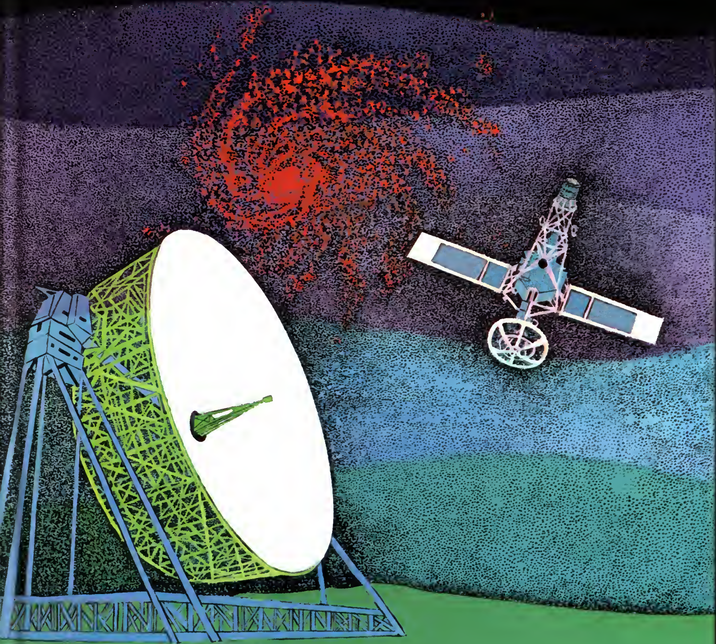

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PLANISPHÆRII COELESTIS HE[...]

Calculatum ad finem Anni MDCC, pro Ævo XVIII præsente:

HEMISPHÆRII SEPTENTRIONALIS Stellæ.

Magnitudines	Primæ	Secundæ	Tertiæ	Quartæ	Quintæ	Sextæ	Nebul.	Summa
Ursa Minor	0	2	1	5	3	8	0	19
Ursa Major	0	6	4	13	7	9	0	39
Draco	0	1	13	13	10	1	0	38
Cepheus	0	0	3	10	9	12	0	34
Camelopardalus	0	0	0	2	6	21	0	29
Fluvis Iordanis	0	1	1	8	8	12	1	30
Bootes	1	0	6	13	7	12	0	39
Corona Borealis	0	1	0	4	6	9	0	20
Hercules	0	0	10	18	10	24	1	63
Lira	1	0	2	3	6	5	0	17
Fluvius Tigris	0	0	0	10	3	40	0	50
Cygnus	0	1	8	14	2	15	0	40
Sceptrum	0	0	0	1	8	8	0	17
Cassiopea	1	0	4	6	6	20	0	37
Perseus	0	2	4	10	18	11	0	45
Aurigae	1	1	0	9	15	20	0	46
Serpentarius	1	0	7	7	6	5	0	26
Serpens Ophiuchi	0	1	8	9	2	24	0	44
Sagitta	0	0	0	3	1	4	0	8
Aquila	0	1	4	1	7	1	0	24
Antinous	0	0	6	1	0	5	0	12
Delphin	0	0	5	0	1	5	0	11
Equuleus	0	0	0	4	0	0	0	4
Pegasus	0	2	3	10	3	7	0	25
Andromeda	0	3	2	9	14	5	0	33
Triangulum	0	0	0	3	2	0	0	5
Lilium	0	0	1	2	4	0	0	7
Coma Berenices	0	0	1	11	1	0	0	13

Zodiaci Constellationes

Aries	0	0	1	3	5	8	0	17
Taurus	0	1	1	1	8	10	0	21
Gemini	0	2	1	2	9	4	0	18
Cancer	0	0	0	1	4	15	1	21
Leo	0	2	7	5	3	8	0	25
Virgo	0	1	6	8	10	14	0	39
Libra	0	2	3	10	7	5	0	27
Scorpio	0	2	0	2	2	1	0	7
Sagittarius	0	0	0	5	1	4	1	11
Capricornus	0	0	3	0	6	8	2	19
Aquarius	0	0	3	5	8	3	0	19
Pisces	0	0	0	5	13	12	0	30
Summa	5	32	118	252	241	364	6	1018

Magnitudines Groote der Sterren	Prima	Sec.	Tert.	Quart.	Quint.	Sext.	Neb.	Summa
Stellæ Hem. Septent. Sterren i. d. Noorder C.	5	32	118	252	241	364	6	1018
Stellæ Hemisph. Austr. St. i. d. Zuid Cirkel	11	35	109	225	224	157	5	766
Summa	16	67	227	477	465	521	11	1784

Summarium Stellarum, cujuscunque magnitudinis utriusq. hemisphærii conficit 1784

De Hoofd som der Sterren in de Noorder en Zuider Cirkel of Hemels helft is van 1784 Sterren

Proportio Stellarum [...]

Merry Christmas to Regon

HEMISPHÆRII MERIDIONALIS Stellæ

Magnitudines	Primæ	Secundæ	Tertiæ	Quartæ	Quintæ	Sextæ	Nebul.	Summa
Balena	0	2	8	13	5	0	0	28
Serpentarius	0	0	1	3	3	0	0	7
Orion	1	5	3	17	20	18	0	64
Eridanus	1	0	10	29	3	3	0	46
Lepus	0	0	4	4	5	1	0	14
Canis Major	1	1	6	2	9	0	0	19
Columba	0	2	0	5	3	0	0	10
Canis Minor	1	0	1	0	0	9	0	11
Unicornis	0	0	3	10	3	6	0	22
Argo Navis	1	7	8	10	15	2	0	43
Hydra	1	0	3	13	12	20	0	49
Crater	0	0	0	8	1	2	0	11
Corvus	0	0	4	1	5	1	0	11
Crux	0	3	1	0	0	0	0	4
Centaurus	1	4	6	13	10	1	0	35
Lupus	0	0	2	8	10	1	0	21
Ara	0	0	1	6	0	1	0	8
Corona Australis	0	0	0	4	3	5	0	12
Piscis Australis	1	0	3	10	3	0	0	17
Grus	0	2	1	2	5	3	0	13
Phœnix	0	2	4	5	2	3	0	16
Indus	0	0	0	6	3	3	0	12
Pavo	4	1	3	4	2	6	0	16
Apus Indicus	0	0	0	3	9	1	0	13
Musca	0	0	0	2	2	0	0	4
Cameleon	0	0	0	0	7	3	0	10
Triangulum	0	1	0	1	3	0	0	5
Hirundo Marina	0	0	0	0	7	1	0	8
Dorado	0	0	1	2	1	1	0	5
Nubes	0	0	0	0	1	1	1	3
Pica Indica	0	0	4	2	3	0	0	9
Hydra	0	0	2	2	10	0	0	14
Nubecula	0	0	0	1	1	0	1	3
Quadratum	0	0	0	2	0	2	0	4
Zodiaci Constellationes								
Aries	0	0	0	0	0	3	0	3
Taurus	1	0	3	7	10	10	0	31
Gemini	0	1	3	4	0	6	0	14
Cancer	0	0	2	2	5	11	0	20
Leo	0	0	0	4	5	8	0	17
Virgo	1	0	0	0	3	7	0	11
Libra	0	0	0	0	0	0	0	0
Scorpio	1	1	10	10	3	3	3	31
Sagittarius	0	3	8	3	6	1	0	21
Capricornus	0	0	2	1	6	6	0	15
Aquarius	0	0	1	6	15	7	0	29
Pisces	0	0	1	0	5	3	0	9
Summa	11	35	109	225	225	157	5	766

Man Probes the Universe

REGON UNSOELD

Colin A. Ronan

with diagrams by Sidney W. Woods

Man Probes the Universe

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Editor	M. H. Chandler
Designer	Arthur Lockwood
Assistant Designer	Brian Lee
Research	Enid Moore

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Contents

1 The Size of the Universe

We are all curious about the things we see and hear in the world around us, and are always asking questions about them. Sometimes we ask idly, and are content with the first rough-and-ready answer we get. But when we are deeply interested we adopt quite a different attitude. If the first answer does not satisfy us we ask more questions, and if possible we put all the answers to some practical test. In fact, we proceed scientifically.

The earliest subject men treated in this way was astronomy, or the study of the stars. Perhaps it all began quite idly when primitive men, tired after hunting, gazed up at the night sky and noticed that certain groups of stars formed fairly simple and easily remembered patterns. In time men would begin to ask questions. Why do we see some groups of stars all the year round and others only in summer? Why do they all seem to move from

east to west across the sky as the night wears on? Where are they in broad daylight when we cannot see them? How is it that a group of stars that sinks below the western horizon just before dawn can rise up over the eastern horizon at nightfall? How far away are the stars? What makes them shine?

Trying to find sound answers to questions about the motions of heavenly bodies kept astronomers busy throughout all the early

The Milky Way, made up of millions of separate stars, is only part of the vast star system, called the Galaxy, to which our Sun belongs. Modern astronomers have discovered millions of other galaxies just as large, and still they have not reached the limits of the universe.

Ancient astronomers were able to make reliable calendars by noting which star group rose first at various times of the year. This Egyptian chart was made somewhere about 100 B.C.

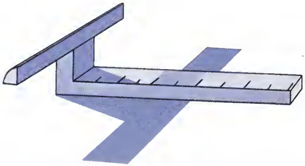
Early men also used the stars as signposts. Each night, in northern lands, they saw the Great Bear group circling around the Pole Star. Walking toward the Pole Star meant traveling north.

civilizations and long afterward. It was not until after the Middle Ages that astronomers agreed that many of the apparent movements of planets and stars are actually due to the movements of the Earth. No really reliable answer to the question about the distance of the stars was given until the beginning of the industrial age, after the first railroads were built. And it is only in the atomic age that astronomers have been able to say with some assurance what makes the stars shine.

All this may look like very slow progress. But we have to remember that although early astronomers did not find the correct answers to all their questions right away, they learned a great deal as they went along. Even though they did not correctly explain why the stars move as they do, they could say that there is a regular rhythm to the movements. This allowed them to forecast the appearance of the night sky for years ahead. They learned precisely which constellations would rise in the east just after sunset at every season of the year, and they used this knowledge to make calendars that enabled farmers to sow their seed at the right season. Thousands of years before the invention of clocks and watches, astronomers could tell the time of day accurately from the position of the Sun, and the time of night from the positions of the stars. Day or night they could use their knowledge of the heavens to find north, south, east, and west.

In very early times astronomers probably did not even try very hard to find answers to questions about the distances of heavenly bodies, partly because they knew it was still a hopeless task. Even to find the distance of the Moon, our nearest neighbor in space, needed thousands of years of progress in mathematics and geography. It could be attempted only after the mathematicians of ancient Greece had learned a great deal about geometry and after geographers had estimated the approximate size of the Earth. Then, soon after 200 B.C., the Greek astronomer Hipparchus was able to make a really close estimate of the Moon's distance. It was only about one per cent different from modern estimates! But to discover how far away even the nearest stars are was a far more difficult task. It could be done only after another 2000 years of progress in many branches of science.

One question must have seemed almost ridiculously simple to the first astronomers: What makes the stars shine? The obvious answer was that "they shine because they are lights burning in the sky." Up to the time electric lights were invented men knew no way of making light except by burning something—torches, candles, wicks soaked in oil, or jets of gas. Since the stars gave out light it seemed perfectly clear that they must be burning too. That simple explanation satisfied the vast majority of people until less than 200 years ago. Then scientists began to ask some awkward questions. Even from written records they knew that the stars had been shining for thousands of years, so why was it that they had not gone out, as an oil lamp or a fire goes out when the fuel is exhausted? Later on geologists proved from skeletons in ancient rocks that life has existed on the Earth for hundreds of millions of years. Since it could not have existed without warmth and light from the Sun, the Sun must have been shining at least as long as that. How could any "fire," even one as enormous as the Sun, burn that long without using up its fuel?



The Sun, nearest of all stars, told men the time of day. At dawn the bar of this Egyptian "clock" cast a long shadow, which shortened as the Sun climbed higher. The changed length marked the passing hours.

Today astronomers have found an entirely new explanation of why the stars shine. The Sun and myriads of other stars, they say, can go on producing heat and light for many millions of years because they are not fires at all, but centers of nuclear reactions.

It would have been quite impossible to give that answer two centuries ago, because people were not yet familiar with atomic theory, and even the word atom had no precise meaning. The idea of atoms was first suggested by the Greek philosopher Democritus, who lived from about 460 to 370 B.C. He believed that all matter was made up of particles so small that it would be impossible to cut them up. Although the idea was interesting, the "atoms" that Democritus imagined were very different from the atoms we know about today, and they did not then seem to be of much practical value. Very little was done about developing the idea until A.D. 1810 when the Englishman John Dalton published his atomic theory.

John Dalton's atoms could not be seen—they were simply the smallest particles that took part in a chemical reaction. They could not be separately weighed, but Dalton believed that the relative weights of different substances were due to the different weights of the atoms of which they were composed. The atomic theory at last made the whole study of chemical reactions truly precise, and since Dalton's time the theory has grown and developed in very many ways. It is of vital importance to the astronomer in his studies of the universe, because without it he could not understand either how stars shine or how they age. Also, he would have very little knowledge of the atmosphere of the planets that orbit the Sun. Without modern atomic theory astronomers could never have made the tremendous progress that they have made in recent years.

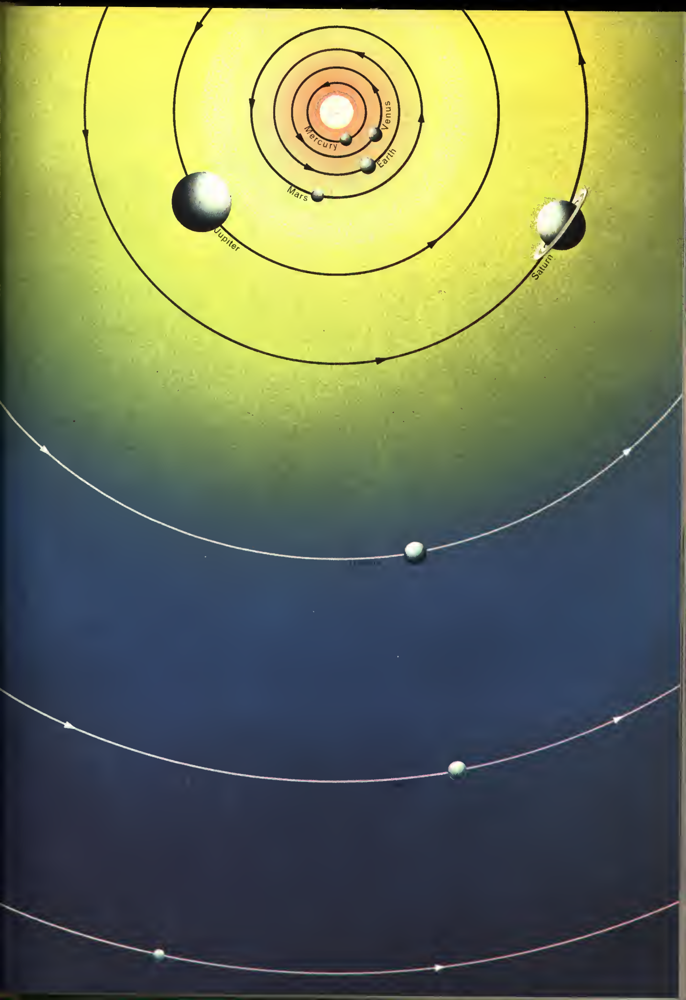
So to understand the astronomy of the 20th century we must look more closely at the atom and its nature. But before we do so let us first try to get some idea of what the universe contains and how large it is, beginning with the Sun and its planets, and then moving ever farther outward.

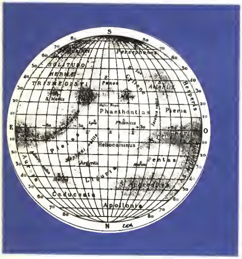
The Sun and its Family

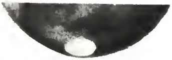
The Sun is the nearest star to us in space, lying at a distance of about 93 million miles. The Earth orbits the Sun once a year, in company with a host of other bodies. Some of them we can see without a telescope in the night sky as they appear to wander to and fro among the stars. These bodies, known as *planets* (from a Greek word that means

From left to right are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto—all drawn to the same scale. Compared with the Sun, even the giant Jupiter is small.

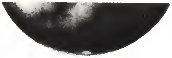
The nine planets, together with the asteroids, all move around the Sun in their own paths, kept in orbit by the Sun's gravitation. The orbits are shown in correct order but not drawn to scale.


Mercury
Venus
Earth
Mars
Jupiter
Saturn





Mars is about half as big as the Earth and nearly 50 million miles farther from the Sun. Icy white caps form around its poles in winter and melt in summer.



Mercury, the smallest planet and the one nearest the Sun, has very little atmosphere. With a powerful telescope its patchy surface can be seen. This map, made in 1933 by E. Antoniadi, names some surface features.

Venus, about the same size as the Earth, is constantly covered with cloud, so we know little about its surface. Since it lies nearer the Sun than we do, and shines by reflecting sunlight, it shows phases like the Moon's.

Right: In 1897 Percival Lowell made this map of Mars. It shows "canals" that he believed were made by intelligent beings. Astronomers no longer think that higher life forms exist on Mars, but there may be plants.

"wanderers"), all orbit the Sun at different distances and at different speeds. Some of them are certainly like the Earth, and are composed mainly of rock and metal, while others probably contain a high proportion of hydrogen and helium. None of them can produce heat and light by atomic reactions as the stars do, and the only reason we can see them at all is that they reflect light from the Sun. The planets, then, do not shine in the same way as the stars.

Compared with the stars, the planets are all cold bodies and every one of them is comparatively close to us in space. The nearest to the Sun is the planet Mercury, orbiting at an average distance of 36 million miles. With a diameter only two fifths as great as that of the Earth, it is a dried-up world, and one which perpetually keeps one side turned toward the Sun. This is because it rotates only once in the time it takes to complete its orbit. Since it lies closer to the Sun than the Earth does, we can see Mercury only in the evening sky just after sunset, or in the morning sky near the time of sunrise.

Next comes the planet Venus, which, like Mercury, can be seen only near sunrise or sunset, and which shares with Mercury the honor of being called the morning star or the evening star. Orbiting round the Sun at a distance of 67 million miles, Venus completes a circuit once every seven months, compared with the three months taken by Mercury. This is because the gravity of the Sun causes a planet to take longer to complete its orbit the farther away it lies. Venus has much in common with the Earth. It is almost the same size and, like the Earth, may have regular seasons as it orbits the Sun. It also rotates on its axis, as all the planets do. But we cannot measure the length of a Venus day (or its rate of rotation) because the planet is completely covered all the time by a thick veil of cloud. This prevents us from seeing the surface of Venus—which may be solid ground, or possibly a vast ocean.

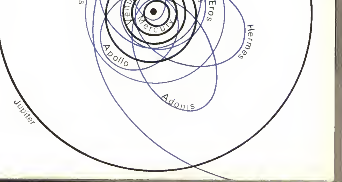
Farther out from the Sun than the Earth are the remaining planets of the Solar System. At a distance of 141 million miles is Mars, which is just over half the size of the Earth

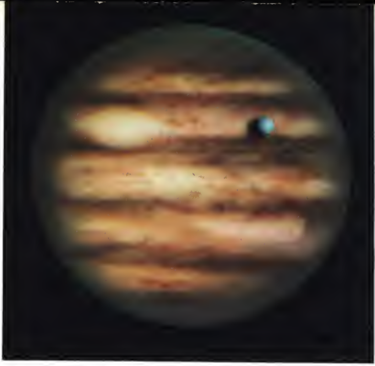
and which takes nearly two years to complete an orbit. Unlike Venus, Mars has only a thin atmosphere, and this enables us to see the planet's surface. This surface is particularly interesting because it shows many markings that some astronomers believe may represent living plants.

Still farther from the Sun, at a distance of between 200 million and 300 million miles, lies a host of tiny "minor planets." These bodies range from 500 miles in diameter down to just a few miles, and all of them are too small to be seen by the naked eye. Because some of them have very elongated orbits and come very close to us, astronomers can use them to get very accurate measurements of distances within the Solar System. These minor planets are also called *asteroids*, which means "starlike." When we see them through a telescope most look like pinpoints, as the stars do, and not like disks of light, which is how the planets appear.

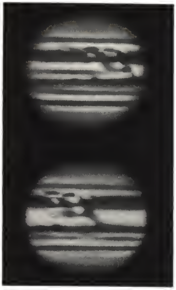
The largest of all the planets circling the Sun is Jupiter, whose orbit lies next beyond those of the asteroids. This giant among the

Here the orbits of five planets (black) are compared with the orbits of eight asteroids (blue). In following their elongated elliptical paths, some asteroids may come very near the Earth—Eros within 15 million miles, Hermes within 500,000. Astronomers can use these "earth-grazers" to make accurate measurements of distance within the Solar System.





Jupiter, which lies next beyond the orbits of the asteroids, is 300 times heavier than the Earth and 11 times as big across. Marks on its dark bands change position over the months.



These two photographs of Jupiter were taken one hour apart. The way the marks on the bands have moved in that time shows that different parts of Jupiter rotate at different speeds.

planets is eleven times larger in diameter than the Earth. If we could put Jupiter on a set of scales and weigh it, we would find that it is 300 times heavier than the Earth. Jupiter appears as a bright star to the naked eye, but through a telescope it appears as a disk crossed by several dark bands. Because these bands change their positions from month to month, it seems clear to astronomers that what they are observing is a thick, cloudy atmosphere. And this is confirmed by the rotation of the markings seen on the bands. The markings move more quickly near the equator of the planet (at a rate of about 9 hours and 50 minutes) than they do near the poles (9 hours and 56 minutes). These different speeds of rotation would be impossible if the planet's surface were solid.

The distance of Jupiter from the Sun is more than 480 million miles, or more than five times the distance from the Earth to the Sun. Yet even so we are as yet nowhere near the boundary of the Solar System. Saturn, the next most distant planet, lies 886 million miles from the Sun—nearly twice as far as Jupiter. Although Saturn is not as large as Jupiter, it is still almost 9½ times as great in diameter as the Earth. Like Jupiter it has a banded, cloudy atmosphere, and it takes about 10¼ hours to rotate on its axis. Saturn has the distinction of being the only planet in the Solar System with a system of rings lying in space above its equator. These rings are composed of myriads of small lumps of rock or ice, or probably a combination of both, circling round the planet in various orbits. Because of the different sizes of the orbits of these pieces, the rings extend from about 9000 to 38,000 miles above the cloudy atmosphere. Yet because of the pull of Saturn's gravity the orbits lie so nearly in one line that the rings are only about 10 miles thick. The rings give to Saturn a strange and unique appearance, and, seen through even a small telescope, it is a beautiful sight.

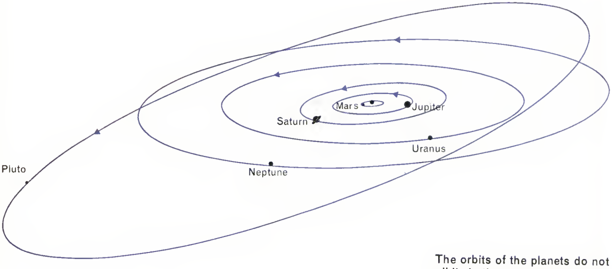
The three remaining planets (except, on occasions, Uranus) can be seen only with a telescope. Uranus, the nearest, lies 1782

Saturn, nearly twice as far from the Sun as Jupiter, is best known for its rings. Even when seen through a small telescope, it is one of the most beautiful objects in the sky.

As the Earth moves in its orbit, and other planets move in theirs, we see them from time to time at various angles. The three photographs of Saturn, below, were taken at six-year intervals.

million miles from the Sun. Neptune, the next, is another 1000 million miles away, while Pluto, the outermost planet, is yet another 1000 million miles off. Through a telescope Uranus and Neptune both appear to have cloudy surfaces; and both are larger in diameter than the Earth—Neptune $3\frac{1}{2}$ times and Uranus almost $3\frac{3}{4}$ times larger. Pluto is very much smaller than either of them, though its size is uncertain.

So far we have mentioned only the nine large planets, including the Earth, and the asteroids. But the Sun's family—the entire Solar System—is much larger than this. Traveling about in space there are many swarms of small, rocky, metallic pieces; and the gravitational pull of the Sun has trapped a number of these swarms so that they now move around it in very elongated orbits. During most of their journeying about the Sun, these captured swarms are invisible. They can be seen only when the Earth crosses the path of one of them, or else when a swarm itself approaches very close to the Sun.



The orbits of the planets do not all lie in the same plane, but are tilted at different angles. Pluto has a steeply inclined orbit and sometimes approaches the Sun more closely than Neptune does.

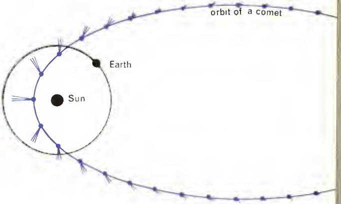
When a swarm does pass close to the Sun, the frozen gas carried along with the rocky, metallic pieces is heated. It then escapes and is set glowing by the radiation of the Sun, which also sends out electrified particles that push this gas away into space. In addition, some of the rocky pieces also reflect sunlight. The outcome of all this activity is that the main body of the pieces can be seen as a bright patch in the sky, with the gases that are thrown into space forming a long glowing tail, sometimes extending for millions of miles. We call such objects *comets*. While they may come to within a few million miles of the Sun at their closest, the other end of their orbits extend out even beyond the orbit of Pluto.

As a comet orbits the Sun, many of the pieces that compose it are spread out along the orbit itself. Some of these pieces gradually collect into rather loose swarms. Such a swarm is not visible as a comet, but it can be observed when the Earth passes through it. The reason for this is that when the swarm and the Earth meet, the rocky pieces move into the Earth's atmosphere. Because of the great speeds at which these rocky pieces are traveling (many miles per second) they become heated by contact with the air. The result is that the pieces glow as they burn up; they also cause the air around them to become electrified so that it glows too.

At each point along the track of one of these falling pieces of rock, this glowing lasts for only a fraction of a second. But often the whole track can be seen for a short time, and it is called a *meteor trail*. The piece of rock itself is called a *meteoroid*. When the Earth passes through a swarm, we are sometimes able to see hundreds of meteors, and such "showers" make a spectacular sight. Most meteor particles, however, are too small to be seen, and astronomers have to rely on other methods of detecting them.

As the major planets orbit the Sun, most of them act as centers of smaller natural satellite systems. Although Mercury, Venus, and Pluto seem to have no "moons"—and the Earth has only one—the remaining planets have various numbers. Mars has two small

Comets are swarms of small, rocky, metallic pieces that follow elongated paths around the Sun. When they are near the Sun, gas carried with the pieces becomes hot and forms a glowing "tail." These photographs of Halley's Comet were taken on nine nights during April, May, and June 1910.



Here the long orbit of a comet is compared with the almost-circular orbit of the Earth. Solar radiation pushes the glowing gas of a comet outward, so that the tail always points away from the Sun.

Sometimes the rocky, metallic fragments that make up a comet become spread out and enter the Earth's atmosphere as a meteor swarm. Friction with the air causes them to vaporize.

All the planets except Mercury, Venus, and Pluto have satellites orbiting around them. Most of these are very small, but Jupiter has four large satellites, shown on the right, as well as eight smaller ones. The only other large "moons" belong to Neptune, Saturn, and Earth.

satellites of about 5 and 10 miles in diameter, which orbit round it in 30 and $7\frac{1}{2}$ hours respectively. Jupiter has 12, four of them about the size of our own Moon and the other eight much smaller. Five of these eight are less than 10 miles in diameter. Saturn has nine satellites, all except one being much smaller than the Moon. Uranus has five while Neptune has only two—the larger one being about the same size as our Moon.

One thing that is interesting about the sizes of the various satellites is this: Although the Earth is the only planet with just one satellite, the one it does have seems to be out of all proportion to the size of the Earth. Some astronomers think of the Earth-Moon as a twin planet! But we cannot say for certain whether the Earth and Moon make up a double planet or not. Many astronomers think that most, if not all, of the satellites in the Solar System were "minor planets" captured by the larger planets thousands of millions of years ago when the whole system was being formed.

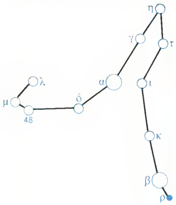
The Distances of Stars

Compared with the vastness of space, the Solar System is a very small and compact collection of celestial objects. Yet to us, accustomed to thinking of the distances we cross as we travel about our own planet, the Solar System seems immense. This is not surprising when we realize that the distance from the Earth to the Sun is almost 4000 times greater than a journey around the Earth at the equator, and that the distance from the Sun to Pluto is equal to about 150,000 trips around the Earth. Such distances are so vast and so far outside our everyday experience that they only puzzle us if we try to state them in miles. And when we come to talk of still greater distances, the figures themselves become far too big to handle with ease. For this reason astronomers have had to find some other yardstick to use instead of the mile; and the most convenient one they have found so far is the distance a beam of light travels in a given time. Light traveling at about 186,000 miles per second, makes the journey from the Sun to the Earth in a little under eight and a half minutes, and from the Sun to Pluto in five and a half hours. So we say that the Sun is eight and a half light-minutes away from the Earth, and that Pluto is five and a half light-hours away from the Sun.

Because Pluto's distance from the Sun is only the radius of our Solar System circle, we must double the distance to arrive at the diameter—11 light-hours. But because some comets extend beyond the orbit of Pluto, we can say that the whole Solar System occupies an area at least 12 light-hours across, maybe much more. Since a journey around the Earth is equal to only one eighth of a light-*second*, we can at once see how immense the Solar System is by our Earth-bound standards.

Yet it is but a speck in the space between the stars. The nearest star to the Sun lies not light-seconds, light-minutes, or even light-hours away, but at a distance of four and a half light-*years*. When we remember that there are nearly 9000 hours in a year, we can see at once that the distance across the Solar System is *very* small compared with the distance of even the nearest star. If we express these two distances in miles, we come up with 7000 million miles for the diameter of the Solar System, and 26 million million miles for the nearest well-known star (that is,

For many centuries men have grouped stars into patterns that reminded them of heroes or animals. On the right we see how a Persian astronomer of the 16th century showed the constellation Perseus. Below is the same group of stars as shown in a modern star atlas.



Astronomers now use the letters of the Greek alphabet (below) to distinguish between the various stars of a constellation.

α	Alpha	ν	Nu
β	Beta	ξ	Xi
γ	Gamma	ο	Omicron
δ	Delta	π	Pi
ε	Epsilon	ρ	Rho
ζ	Zeta	σ	Sigma
η	Eta	τ	Tau
θ	Theta	υ	Upsilon
ι	Iota	φ	Phi
κ	Kappa	χ	Chi
λ	Lambda	ψ	Psi
μ	Mu	ω	Omega

This is the edge-on view that a distant observer would have of our Galaxy. Dust and gas separating the Sun from the center of the Galaxy prevent us from seeing the bright nucleus.

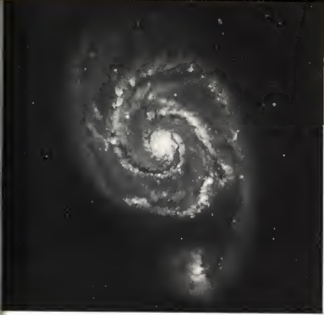
Alpha in the constellation of the Centaur, or *α Centauri,* which is visible only to people living in and south of the tropics). When we come to the distances of other stars we shall find that four and a half light-years is "just around the corner." For example, the brightest of all the stars we can see in the sky, Sirius, is eight light-years away, and the star Vega is 26.5 light-years away; yet even these are near neighbors. Arcturus is 36 light-years away, Capella 45 light-years, and Aldebaran 68 light-years, but even these cannot be considered *distant* stars.

Only when we come to stars like Spica and Antares, at 220 and 520 light-years away respectively, are we dealing with stars that we can really call far off. Even so, we have not begun to exhaust our list of bright stars. Rigel, in the constellation Orion, lies 900 light-years away. This means that the light from it which reached us last night began its journey 900 years ago, roughly the time that the Normans conquered England. The universe of stars, then, is very much vaster than we might imagine when we glance casually up at the night sky.

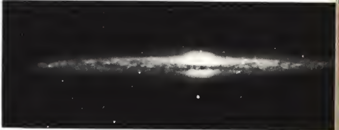
We have seen that the planets form a compact group and move around the Sun in a systematic way. What of the stars themselves? Can we find any system or any arrangement in them? How, exactly, do they move? How far in space do they extend? Questions of this kind, which puzzled astronomers for thousands of years, have been answered only in the past century. Of course, even when men still lived in caves they recognized the fact that the stars always appear to remain in the same positions with respect to one another. It was this fact that enabled early men to group the stars in patterns that reminded them vaguely of the heroes and heroines of legend or of the wild animals they knew. But these groups, or constellations, are only patterns as seen by an observer on the Earth. They are not made up of stars that are actually close together in space. They only appear to be close together. It is only since astronomers discovered that the stars themselves move and since they learned how to measure star distances that we have begun to recognize a genuine pattern and system in the stars.

The Milky Way

Astronomers now know that the whole conglomeration of stars that we see in the



Seen face-on our Galaxy would look much like the Whirlpool Galaxy in Canes Venatici.



There are other galaxies similar to our own that we see almost exactly edge-on, like NGC 4565 (above) located in Coma Berenices. The Andromeda Galaxy (below) is similar in size and shape to our own Galaxy, but we see it at an angle.

night sky is part of one gigantic system. The shape of this star system is rather like two dinner plates turned face to face with their rims touching and with a bulge in the center. The Solar System is nowhere near the center of this star system, but lies about two thirds of the way toward the outer edge. The stars are most densely packed in the central bulge and in the flat level portion between the rims of the "plates"—that is, in the central plane. You can see this for yourself by looking up at the stars on a clear night. A hazy band of light stretches across the heavens from one side to the other, as shown in the artist's impression on pages 10 and 11.

Early men certainly noticed this band of light; many legends grew up about it, and gradually it came to be widely known as the *Milky Way*. After the invention of the telescope, astronomers could see that this hazy band was made up of a vast number of separate stars, and we now know that this band of stars represents the central plane of our Galaxy.

Even though the Solar System lies near one edge of this star system, the Milky Way is seen to stretch as an almost straight band across the entire sky. This is so both north

and south of the equator, and it means that the Solar System lies in the central plane of the Galaxy, so that whichever way we turn we can see this dense collection of stars. When we look out into the sky in a different direction from the Milky Way, we see that the stars are not in a dense mass. Instead they are more scattered about the heavens. This is because we are then looking away from the central plane and out through the more thinly populated parts of the Galaxy. The Milky Way is, in fact, a guide showing us the direction in space of the central plane of the star system of which our Sun is a member star, and this is the reason why the system is called the Galaxy, a name that comes from the Greek word for milk.

Compared with the great distances of the stars we mentioned earlier, our Galaxy is immense. From "top to bottom"—that is, through the thickest part of the central bulge —it is 20,000 light-years thick. And from one edge across to the other the distance is 100,000 light-years. But these measurements do not take into account the distances of certain stars that are scattered above and below the Galaxy itself. A few of these stars are separate ones; but most form great clusters. Some clusters, called globular clusters, form a kind of halo around the Galaxy. Each individual cluster is made up of thousands, or sometimes tens of thousands, of stars closely packed together into the shape of a ball or globe. The nearest one to the Solar System is about 20,000 light-years away.

Our Galaxy, then, consists of stars, most of which lie in the central plane or in the central bulge, together with a halo of separate stars and globular clusters. However, in our own century astronomers have finally proved that the Galaxy also contains a considerable amount of gas.

Seen through a telescope, some of this gas takes the form of great glowing clouds called *nebulae,* from the Latin word for clouds. The most famous of all the nebulae is the large gas cloud in the constellation Orion. To the naked eye it appears as a tiny hazy patch of light in the middle of the three stars forming Orion's sword. But through even a small telescope it becomes an exciting object to look at. The stars of the rather spread-out cluster known as the Pleiades are all surrounded by glowing gas. If you sweep the heavens with a telescope, you will soon discover that there are far more nebulae than you can see with the naked eye. The Milky Way itself has a very large number of them. For example, nebulae such as those where Sagittarius crosses the Milky Way cover areas measuring hundreds of light-years, and some have bright stars embedded in them.

In many bright gaseous nebulae there are dark "lanes" and patches. In the Milky Way there seem also to be dark rifts among the stars themselves, as if one were looking at holes in the starry background. The dark patches, both in the Milky Way and in the bright gaseous nebulae, are due to gas that is not glowing, or to dust. As we shall see later, astronomers can distinguish the non-glowing gas from the dust, but here we are concerned only with the fact that both of them completely blot out the light from stars and bright nebulae that lie beyond them. This blanketing effect in the Milky Way deprives us of what must be a grand sight. Because of the great number of nebulae lying between us and the center of the Galaxy we are not able to see the brilliant array of closely packed stars that form the nucleus of the Galaxy. Our telescopes reveal only those stars that lie this side of the dense center.

In spite of the problems raised by this dust and dark gas, we have been able to discover that our whole Galaxy is rotating. The Sun, which is quite an ordinary star in the Galaxy, takes part in this cosmic rotation, carrying our Earth and all the other planets along with it. Like other stars nearby, the Sun moves through space at a rate of 150 miles per second, a speed that would take us once around the Earth in about two and a half minutes. Yet the Galaxy is so enormous that the Sun spends 225 million years completing one circuit. This immense period of time, appropriately called a cosmic year, is beyond our powers to imagine. But we can gain at least some idea of what it means when we realize that two cosmic years ago life on

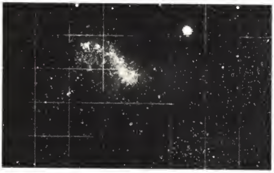
In addition to millions of stars, our Galaxy also contains many glowing clouds of gas, or nebulae. This one, the Orion Nebula, can be seen with the naked eye. In many bright gaseous nebulae, and also in other parts of the Milky Way, there are dark patches of non-glowing gas or dust. These blot out our view of stars that lie far beyond.

Earth was only just beginning, and less than one two-hundredth of a cosmic year ago, man appeared on the scene.

All the stars of the Galaxy are taking part in this cosmic rotation, although their speeds vary. Those stars closer to the center of the Galaxy generally move along more quickly than those near the outer edge. This motion around the Galaxy forms the main motion of the stars, but each one also carries out small local motions of its own. In other words, they do not move around the center of the Galaxy as one solid mass. It is rather like a rush-hour crowd moving toward a subway. Although everyone is going in the same general direction, the path of each individual person is made up of many distinct motions, some to the left and some to the right, as he dodges traffic or other pedestrians. So it is with the stars in our Galaxy. The general direction is one around the dense central nucleus.

Beyond the Milky Way

As we saw earlier, our star system is 100,000 light-years in diameter and 20,000 light-years "deep" at its central and thickest part. Does the Galaxy contain the entire universe of stars, gas, and dust visible to us?



Small Magellanic Cloud

Large Magellanic Cloud

The nearest galaxies beyond the Milky Way are the Magellanic Clouds, both of which are smaller than our Galaxy.

The answer is no, for astronomers have discovered that our Galaxy is only one of many millions of galaxies. These other galaxies extend into space in every direction as far as we can see, even with our largest telescopes. Like the Milky Way, they all contain stars and, presumably, planets—while some contain much dust and gas as well. The only planets we have actually observed, however, are those of the Solar System, but this does not mean that the Sun is the only star in the universe to have a planetary system. It means only that our telescopes are not yet powerful enough to detect any other planets, if they do exist.

The countless galaxies that we can observe lie so far off in space that even the 100,000-light-year diameter of our own Galaxy begins to pale into insignificance. The galaxies nearest to us are visible only from south of the Tropic of Cancer. They are known as the Magellanic Clouds, named in memory of the great explorer Ferdinand Magellan, who was the first to record them during his voyage around the world more than 400 years ago. The Magellanic Clouds look very much like pieces broken off from the Milky Way. They are, however, separate galaxies, smaller than our own, and they lie 150,000 light-years away from us.

Yet even the Magellanic Clouds are close neighbors by the standards of the entire universe. They belong to the same "local" cluster of galaxies as does our own star system. This cluster contains at least 13 galaxies, possibly 16. The Milky Way seems to lie at one edge of the cluster, and near the center is the only galaxy—apart from the Magellanic Clouds—that can be seen without a telescope. This galaxy appears to the naked eye as a dim, hazy patch of light in the constellation of Andromeda; but when photographed through a large telescope it becomes so clear that we can see some of its separate stars. This Andromeda Galaxy lies almost two million light-years away. The light we see from it tonight began its journey long before the first men lived on the Earth.

The entire local cluster of galaxies, which is very oval in form, covers so great a volume

in space that it is difficult to find any comparison that will help us to imagine its size. We are not certain about the actual figures, but the cluster seems to take up an area of at least four million light-years in length and about half this in breadth. Its thickness is about 600,000 light-years.

When we use telescopes to explore even farther into space, beyond our local cluster of galaxies, the distances become unimaginably great. We can do little more than compare figures with figures. Other galaxies and clusters of galaxies, 50 million and 100 million light-years away, are not uncommon. Astronomers now know that galaxies can be observed as far into space as their telescopes can penetrate. By using the largest modern telescopes, fitted with cameras, we can learn something about galaxies as far away as about 3500 million light-years.

Within the last two decades a new means of "seeing" even farther into space has been developed—the radio telescope. These instruments are really nothing more than very sensitive radio receivers with special aerials. Their purpose is to receive not the light but the radio waves sent out by stars and gas, both in our own Galaxy and in other galaxies. With radio telescopes astronomers can probe much more deeply into space than they can with optical telescopes. It is these new instruments that are helping the astronomer piece together a picture of the whole universe—a universe to which we can at present set no limits.

Changing Views of the Universe

Our modern picture of the universe shows us that it extends even farther into space than we can penetrate with the largest optical telescopes or the latest radio telescopes. We think of the stars as vast thermonuclear reactors. We can study the chemical structure of interstellar gas and examine the gases in the atmospheres of the planets. In short, modern science has given us many precise details about the construction of the whole universe. But is the picture we build up from these details the final one—one that will never be changed?

It has taken mankind many hundreds of years to construct a "blueprint" of the universe, and along the way he has had to discard many of his ideas. The fact is that we can have no assurance that our present "blueprint" of the universe will not change. It is

Astronomers of long ago were not greatly concerned about distances. They wanted mainly to explain the motions of celestial bodies. The ancient Egyptians pictured the goddess Nut arched over the Earth to form the sky. Each day a boat ferried the Sun across this arch from east to west.

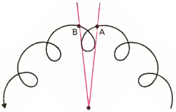
bound to; but this thought should not alarm us. It is important to remember that early astronomers found answers to many of the questions we are asking today. Although they were not the same answers as a modern astronomer would give, the answers were satisfactory. We probably would have come to the same conclusions had we lived two or three thousand years ago, and we cannot be certain how our present views will appear to astronomers living two or three thousand years from now.

The answer to questions about the shape of the universe once seemed a very simple one. Obviously it was shaped like a dome with the stars stuck on the inside. "Obviously," because you have only to look up at the night sky to see for yourself. Because the distances of the stars and planets were quite unknown to early astronomers, it seemed perfectly sensible to think of the stars as all being fixed on the inside of such a gigantic dome.

So far as the Earth was concerned, men first of all believed it to be flat. Then, in Phoenician and early Greek times, this idea began to be challenged. During this time seamen were making long voyages north and south along the Atlantic coasts of Europe and Africa, and they found that different groups of stars could be seen from different latitudes. North of the tropics, for instance, they could see the Pole Star but not the Southern Cross; south of the Tropic of Capricorn they could see the Southern Cross but not the Pole Star.

People also noticed that during eclipses of the Moon, which occur nearly every year, the Earth's shadow cast on the Moon always had a curved edge. All this evidence strongly indicated that the Earth was round, not flat. Even though no one had yet sailed completely around the world, astronomers generally agreed by about 400 B.C. that our planet was shaped like a globe.

Ideas about the heavens had also changed a little by this time. Astronomers were no longer content to consider them just as a dome. Instead, they thought of the stars as being fixed to the inside of a huge sphere enclosing the Earth. Coupled with the knowledge that the Earth was not flat, this allowed them to explain the motions of the Sun, Moon, and planets.



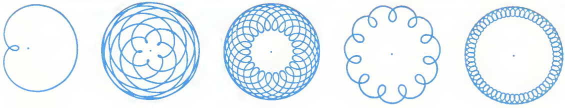
Because we see the planets from a moving observatory (the Earth) they seem to move in looped paths. One night we may see a planet in direction A. Later we see it in direction B. It then moves back to A again before resuming its counter-clockwise motion.

The photograph opposite, taken at Munich planetarium, shows just how complicated the paths of planets look when plotted against the background of fixed stars. Below are the patterns that five of the planets trace.

They knew that the Sun rose approximately (although seldom exactly) in the east, set approximately in the west, and moved around the sky in a curved path. Naturally enough then, they concluded that the Sun circled the Earth, completing its journey once every day. Even though we now know that this idea is not correct, we still find it a useful one. When astronomers work out the times of sunrise and sunset or forecast the times of the eclipses, they still find it simplest to think of the Sun as orbiting the Earth.

The early astronomers also believed, quite rightly, that the Moon orbited around the Earth, and that it was closer to us than the Sun was. They could see this quite clearly whenever the Moon came between them and the Sun at times of solar eclipse.

Early attempts to measure the distance of the Moon and the Sun were not very



accurate. But they did at least confirm the idea that the Moon was considerably nearer than the Sun. Then in the second century B.C. the Greek astronomer Hipparchus made a very good estimate of the Moon's distance, as we saw earlier. So at that stage, beliefs about the Moon's path and its distance were not so very different from our present ideas.

But what of the planets? What paths did they follow? Here was a complex problem, because the planets, unlike the Sun and Moon, do not trace simple curves across the sky. Mercury and Venus always keep close to the Sun and seem to move from one side of it across to the other. On the other hand, Mars, Jupiter, and Saturn were seen to move more slowly across the sky, stopping now and again, then retracing part of their path, then stopping once more before going forward again. In brief, these planets seem to move across the sky in loops as well as in curved paths.

Explaining all these motions of the planets in a satisfactory way was the biggest problem early astronomers had to face. The stars seemed to present no very great difficulties. After all, they always kept their same positions in relation to each other, and they all moved once around the heavens every day. It seemed perfectly reasonable to think that the sphere to which they were attached spun round the Earth once every 24 hours. But a simple circular motion of this kind was not enough to explain the paths of the planets.

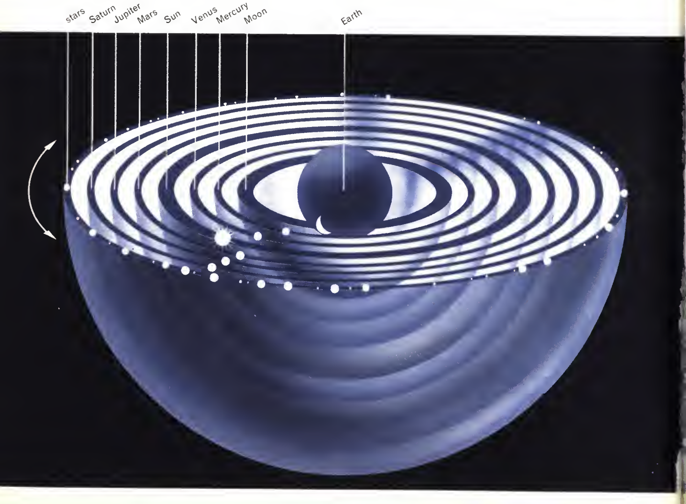
It was generally agreed that the planets must orbit the Earth in circular paths—but in addition they must be moving round and round in a small circle as well. The large circle was called a *deferent* and the small one an *epicycle*. This explanation seemed fine. It accounted for the main motions of the planets and for the apparent loops in their paths. In fact, the system of deferents and epicycles seemed so good that it was used from about 230 B.C. until A.D. 1540—a period of more than 1700 years. But toward the close of that period the system began to weaken. As more and better observations

were made, the positions of the planets could be plotted with much greater accuracy. This made it necessary to add more and more epicycles in order to account for the planets' irregular motions. Even so the same basic explanation remained unchanged.

The astronomers of ancient Greece and other early civilizations also tried to explain *why* the heavenly bodies move, what they are made of, and what holds them up in the sky. At that time there was no idea of gravity to help them, so they had to find other explanations. In general they agreed that beyond the sphere of the stars there must be another sphere. It was called the *primum mobile*, or the prime mover, and its rotation provided energy for the rotation of the rest of the heavens. The *primum mobile*, then, was the outer sphere, which moved the sphere of the stars. The sphere of the stars in turn moved the sphere of Saturn (at that time thought to be the most distant planet). The sphere of Saturn moved that of Jupiter and so on, down to the sphere of the Moon.

The explanation about what the heavenly bodies are made of was even simpler, but still quite satisfactory in its day. Astronomers had correctly supposed that the Sun, Moon, stars, and planets had been visible since the earliest times and had always traveled across the sky in the same way. In brief, the heavens appeared changeless. All celestial bodies, then, must be eternal—as indeed they are in comparison with the lives of human beings, or even with the durations of empires and civilizations. If they were eternal they could not change or decay, so astronomers began to think of celestial bodies as being made of a special kind of substance, something quite different from the substances found on Earth.

One question still remained: Why did celestial bodies stay up in the sky and not fall down to Earth? All things, celestial bodies included, were supposed to have their own "natural place" in the universe. The natural place of heavy substances was the center of the Earth, and this explained why things fell downward; they were simply seek-



ing their "natural" place in the universe. In the days before there was any understanding of gravity this was as good an explanation as one could hope for. Flames, on the other hand, went upward because their "natural" place lay above the air. And the Sun, stars, Moon, and planets remained in space because this was the "natural" place that they had been made to occupy.

All this sounds very far removed from the ideas we hold today. We now know, as we shall see in the next chapter, that the stars are not made of substances different from those we find on Earth. In fact, everything in the universe is made up of the same kinds of atoms that we can study in our own laboratories. We also know that this material is very far from being "changeless" and "eternal". Yet this knowledge of the nature of the stars is all new. Most of it has been discovered only within the last 100 years. If we had lived in Greek times we would have been quite satisfied with the picture of the universe astronomers then accepted.

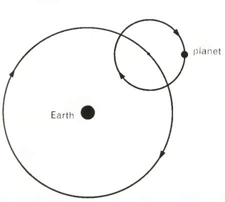
One Greek scientist, named Aristarchus, who lived in the third century B.C., believed that the Earth and all the planets move around the Sun. But he could not prove it so he found very few people willing to believe him. Many hundreds of years passed before enough accurate observations of the planets had been collected to weaken the idea that everything revolved about the Earth.

In 1543 the Polish astronomer Nicolaus Copernicus published a book in which he revived the belief that the planets orbit around a point near the Sun, not around the Earth. There were still no observations to prove the theory, but this time it found favor with other astronomers. Even though the Copernican system used deferents and epicycles it made all calculations of the future positions of the planets much simpler.

Less than a hundred years after the time of Copernicus, the German astronomer Johannes Kepler worked out a series of calculations about the orbit of Mars. As a result, he found that the whole idea of

Early Greek astronomers saw the heavens as a series of spheres with the Earth at the center. The outer one, the "prime mover," moved the sphere of stars. This moved the sphere of Saturn, which moved the sphere of Jupiter, and so on.

Ptolemy (about A.D. 150) taught that the Earth stood still while the Sun moved around it. Each planet moved around the Earth in a large circle, as well as moving round and round in a small circle.



In 1543 Copernicus published a book giving an important new idea. He believed that the Sun remained still and that the Earth moved around it.

deferents and epicycles could be done away with. Mars, he discovered, moves around the Sun in an oval path called an ellipse; surely the other planets must move in the same way, and this is the conclusion Kepler finally reached. But nobody yet knew *why* the planets should move in ellipses. It was not until 1687 that the answer was found—when the Englishman Isaac Newton discovered the law of universal gravitation. Newton showed that gravity *demanded* that the planets should move either in circles or in ellipses around the Sun. Here at last was a theory that made sense of all man's existing knowledge of the universe and that also showed that all celestial bodies, wherever they are, behave according to the laws of physics. A huge step forward had been made in man's thinking on astronomy.

While Kepler and Newton were at work on the theory of how the planets move, other astronomers were busy improving observing instruments. In the late 16th century the Danish astronomer Tycho Brahe made more accurate instruments and better observations than anyone before him. But the greatest advance came in 1609, when the Italian scientist Galileo Galilei first used the newly invented telescope to look at the heavens. At last astronomers were able to get a more detailed view of the Sun, Moon, and planets. With this new view came the realization that many early ideas would have to be changed. The Moon, for instance, was not a smooth globe, but had mountains and valleys like those on the Earth. Other planets beside the Earth had moons of their own. The Sun's surface often showed dark spots that, as they moved, enabled astronomers to measure the speed of the Sun's rotation. Even more important, astronomers could see far more stars than had ever been seen with the naked eye. Telescopes showed astronomers that the Milky Way was not just a hazy band of light, but was made up of myriads of stars. Gradually the whole study of astronomy was broadened and the stars rather than the planets became the main center of interest.

Here we see some of the men who helped to shape our view of the universe. Ptolemy (left) dominated ideas on astronomy for 1400 years. Copernicus helped open a new era.

Tycho Brahe, who lived from 1546 to 1601, measured positions of stars more accurately than anyone before him.

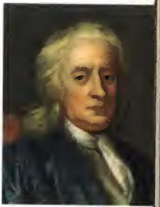
Why We Study the Stars

With the help of telescopes astronomers were soon bringing new facts together, and this gave rise to new theories. In turn, the new theories demanded better observing instruments and extensive observations so that all new ideas could be tested. In this way theory and observation constantly helped each other forward.

Here is one example of how this partnership has worked. Kepler had shown that the planets move about the Sun in ellipses, and Newton's theory of gravitation had shown that those are the very paths that the laws of physics demand. But there was still no way of proving by observation that our own planet actually does move in an ellipse around the Sun. If the Earth really does move around the Sun once a year, then when we look at the nearer stars against the background of more distant stars, we ought to be able to detect a tiny yearly motion in them.

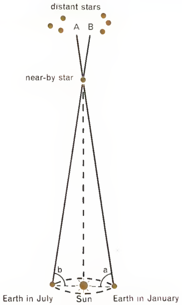
In the 18th century the English astronomer James Bradley set out to discover this very small motion. In the course of his observations he found that the Earth's axis makes a kind of "nodding" motion in space. He realized that he must allow for this nodding motion before he could detect the particular motion of the nearer stars. Now the interesting thing about all this is that the nodding motion that Bradley discovered could be explained only by Newton's theory of gravitation. So here a new set of observations helped to confirm an important theory.

As he continued his observations Bradley found that a star in the constellation Draco (the star γ Draconis) did seem to shift its position against the background of more distant stars—but, unfortunately, not in just the way he expected. Then in 1727 he found that the shift of this star, and of other stars as well, *could* be explained. Beyond doubt the shift was due to the Earth's motion in space. At last someone had discovered proof of the Earth's motion. A good theory had encouraged Bradley to make his observations and these had proved the theory correct.



Galileo (above, left) lived from 1564 to 1642. He used mathematics to study how things move. Newton (1642 to 1727) took this idea further, applying it universally.

Kepler (1571 to 1630) discovered three laws of planetary motion and proved that the orbits of the planets are ellipses.

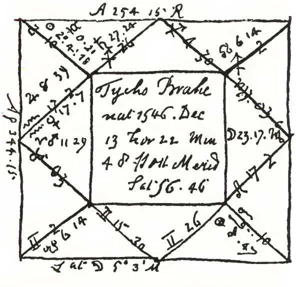


At one season of the year we see a nearby star in direction A. Six months later the Earth has moved halfway around its orbit, and we see the star in direction B. The diameter of the Earth's orbit is known, so if we can measure angles *a* and *b* we can work out the star's distance.

So we see that the astronomer makes his observations and forms his theories. His theories lead him to make new observations and these in turn cause him to build new theories. And this is just what we meant earlier when we said that we can have no assurance that our present "blueprint" of the universe will not change.

But what, you may ask, is the purpose of it all? Does knowledge about the size, shape, structure, and motions of the bodies making up the universe really matter?

Apart from wanting to know such things simply for the sake of knowing them, in all ages men have been urged on because they had to find practical answers to practical questions. In prehistoric times, when man was a nomad and hunter, he needed to study the phases of the Moon to help him in his night hunting, and to work out a Moon calendar so that he could fix the times of important tribal and religious ceremonies. Thousands of years later, in Egypt and Mesopotamia, when men settled as farmers, they



When men settled down as farmers they needed to study astronomy in order to make a calendar closely related to the seasons. Some 3000 years ago this stone carved with signs of the Zodiac marked Babylonian boundary zones.

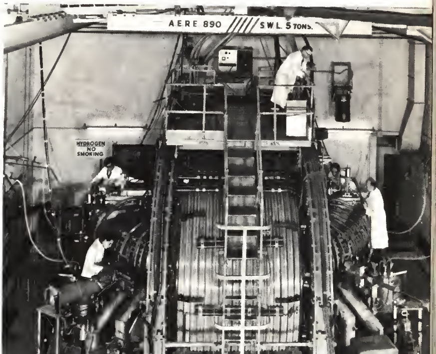
The study of astronomy was also encouraged by the idea that a man's life was influenced by the positions of stars when he was born. The horoscope of Tycho Brahe shows the year, month, day, hour, and minute of his birth.

needed to know the changing positions of the rising and setting Sun against the whole starry background. They needed this knowledge in order to make a calendar that would be closely related to the seasons of the year, so telling the right time to plant seeds.

In very early times there was also a general belief that the stars influenced human destiny, and that a man's future could be foretold from a knowledge of their positions at the moment of his birth. The astrologers who made such predictions needed to know a great deal about the heavens. Many ancient astrologers, then, were skilled astronomers too. Later, the needs of shipping also acted as a spur. Phoenician and Greek seamen who first ventured far north and south in the Atlantic needed to know their latitude. They could find latitudes only from a knowledge of the Sun and the stars. Then, from the time of Columbus onward, when ships began to make far longer east-west ocean crossings, mariners needed an even more exact knowledge of the heavens to help them determine longitude at sea. The Royal Observatory at Greenwich, England, was founded in 1676 for the definite purpose of "perfecting navigation." One of its main tasks was to make observations and compile tables showing the future positions of the Sun, Moon, and stars.

Today, astronomy is closely related to many other sciences, among them chemistry and physics. We can see how the astronomer helps other scientists if we consider what he can discover about the stars themselves.

He wants to know what they are made of and how heat and pressure act on stellar material. The temperatures and pressures in stars are so great that it is impossible for us to imitate them in an Earth-bound laboratory. Even if we could, the laboratory would be vaporized at once. The astronomer, then, must use celestial laboratories—the stars themselves. In them he can discover how substances we know on Earth behave under extreme conditions, and so learn more about the substances themselves. This knowledge is important in all branches of science.



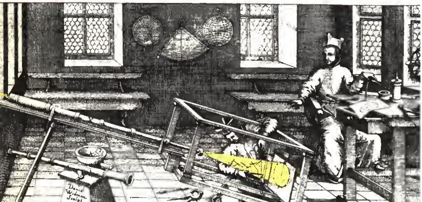
Today much that we learn from the stars can be applied to scientific developments on the Earth. Zeta (Zero Energy Thermonuclear Assembly) is one of the devices used in research into thermonuclear processes similar to those that occur in the Sun. For a few thousandths of a second it can produce temperatures of about a million degrees Centigrade. Physicists believe that temperatures 100 times greater will be needed before such devices can produce really large-scale fusion.

2 How Stars Shine

Just how much do we know about the inner workings of the stars? And, considering that they lie millions upon millions of miles away, how do we gather information about them? Even when viewed with the largest telescope, the brightest stars in the night sky appear only as tiny dots of light. They do not reveal themselves as small globes as most of the planets do. Obviously these pinpoints cannot help us to describe what a star looks like from nearby. Yet that is just what we want to know if we are to build up a really full picture of how the stars shine.

Fortunately there is one star near enough for us to study in great detail—the Sun. Only 93 million miles away, it is 200 thousand times closer than the next nearest star, and millions of times closer than most of the bright stars we see at night. The Sun also has another advantage as the starting point for our investigations. It is just an ordinary star—neither exceptionally big, nor extremely bright—and it seems to be a star of middling age. In fact it is typical of millions of other stars, and much of what we learn from it applies to them too.

The Sun is 864,000 miles in diameter—about 109 times larger than the Earth. At least, this is the diameter of the great globe of gas from which the Sun's light comes. The bright "surface," mainly of hydrogen and helium gas, has a temperature of 6000° C. and is called the *photosphere*. When we talk of the photosphere as a "surface," however, we have to remember that a globe of gas has no hard-and-fast edge like the solid surface of our own rocky planet.



The only star we can study comparatively closely is the Sun, but what we learn from it applies to millions of other stars as well. Some 350 years ago, Christopher Scheiner used an early telescope to produce a small image of the Sun on a screen. Today, with excellent photography and powerful telescopes to help us, we can build up detailed pictures of the Sun's surface like that shown opposite.

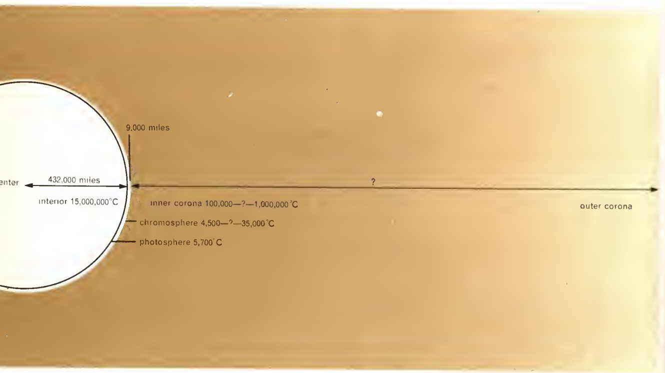
The Atmosphere of the Sun

Above the photosphere (and perhaps forming part of the *chromosphere*) lies a shell of somewhat cooler gas—about 5000° C. and extending outward about 300 miles. For reasons that we shall see later, it is called the *reversing layer*. It consists mainly of hydrogen, but it also contains small amounts of other elements. The gas of the reversing layer is spread out very thinly, its pressure being only about one thousandth as great as the pressure of the air on our own planet at sea level. We can think of this layer as the bottom of the Sun's atmosphere.

Extending above the reversing layer for a height of 6000 miles lies a shell of pink-tinted gas known as the *chromosphere,* or color sphere. Ordinarily we cannot see the chromosphere, but it does become visible during a total eclipse of the Sun, when the Moon completely blots out the glaring light of the photosphere. With the help of an instrument called a coronagraph (which makes an artificial eclipse) it can also be seen from observatories located high in the mountains, such as at the Harvard University Observatory at Climax in Colorado. The chromosphere is made up of the same kinds of gases that we find in the reversing layer except that it contains more hydrogen. The temperature of the chromosphere's gases is about 5000° C., about the same as the reversing layer.

The top and most extensive part of the Sun's atmosphere is the *corona,* or crown, named for the way it seems to crown the entire area around the Sun with a pearly light during a total eclipse. Like the chromosphere, the corona is visible only at times of total solar eclipse, or else in the coronagraph. Even then it is not easy to see because it gives off only half as much light as the full moon.

The temperature of the corona is about 1,000,000° C., but to understand this figure we must be sure of what we are measuring. Temperatures of gases refer to the motions of the atoms in the gas; and for atoms in the corona the temperature is very high—meaning that the atoms are rushing about at great speeds. Even so, the gas of the corona is not "hot," because it is spread out so thinly. If it



This diagram summarizes what astronomers have learned about temperatures deep inside the Sun, at its surface, and in the main layers of its atmosphere.

were possible to stand in a room filled with it you would freeze to death.

How far into space the corona extends is still something of a puzzle. The inner corona, which is rather more yellow than pearly white in color, is no mystery, for we know that it lies within 100,000 miles of the Sun's disk. It is the outer corona that is puzzling. During a total eclipse of the Sun it can be seen and photographed, but its shape and size often differ from one eclipse to another. Sometimes it is roughly circular in outline, sometimes oval, and sometimes quite irregular. Often there are long, bright rays—sometimes curved and sometimes straight—that stretch at least a million miles into space, and perhaps two million or more. Yet for many years astronomers have believed that even this distance does not represent the absolute limit of the outer corona.

Within the last 10 years special studies of the corona have been made, and those involving radio telescopes have been particularly successful. Astronomers now know that the outer corona extends at least seven million miles into space in all directions, and 23 million miles outward in the direction of the Sun's equator Yet even these figures are not final. Some scientists have now suggested that the extremely thin outer fringe of the corona may extend as far out as the Earth. If this really is so, then we are orbiting inside part of the Sun's atmosphere, as are the two inner planets, Mercury and Venus.

We may never know exactly where the corona ends simply because we cannot really think of any section of the Sun's atmosphere as having firm and definite limits. The photosphere merges into the reversing layer (which some astronomers do not even regard as a separate shell of gas), and the reversing layer merges into the chromosphere. The chromosphere itself, which has a spiky edge rather like a neglected lawn, certainly has an irregular boundary where it meets the corona; and between the inner and outer corona no firm line can be drawn. This all results from the fact that the Sun is a glowing ball of gas and has no solid surface that we can fix as a definite boundary.

This photograph, taken in 1947, shows the corona, the outermost and greatest layer of the Sun's atmosphere. It extends several million miles into space.

In 1952, when there were fewer sunspots on the Sun's surface, the corona looked very different. Such changes make it hard to measure the corona with precision.

Photosphere and Sunspots

The merging layers of the Sun's atmosphere are of great interest to astronomers, partly because they can provide many clues about what is happening in the dense interior. Yet the atmosphere does not tell the whole story. Much information about the deep inside of the Sun comes from studies of the photosphere, which in most photographs shows very little detail except for large dark spots that appear to move across it from time to time.

Fortunately there are more reliable ways of discovering what is happening in the photosphere than ordinary photographs can tell us. It is now possible for unmanned balloons to carry telescopes equipped with cameras to great heights above the Earth's surface. At heights of 80,000 feet or more the Earth's atmosphere is very thin, and this enables us to take exceptionally clear photographs. All of these high-altitude photographs show that the photosphere does not have the smooth, unruffled surface shown in ordinary photographs. Instead, we see a mottled surface looking rather like a layer of rice grains in constant motion.

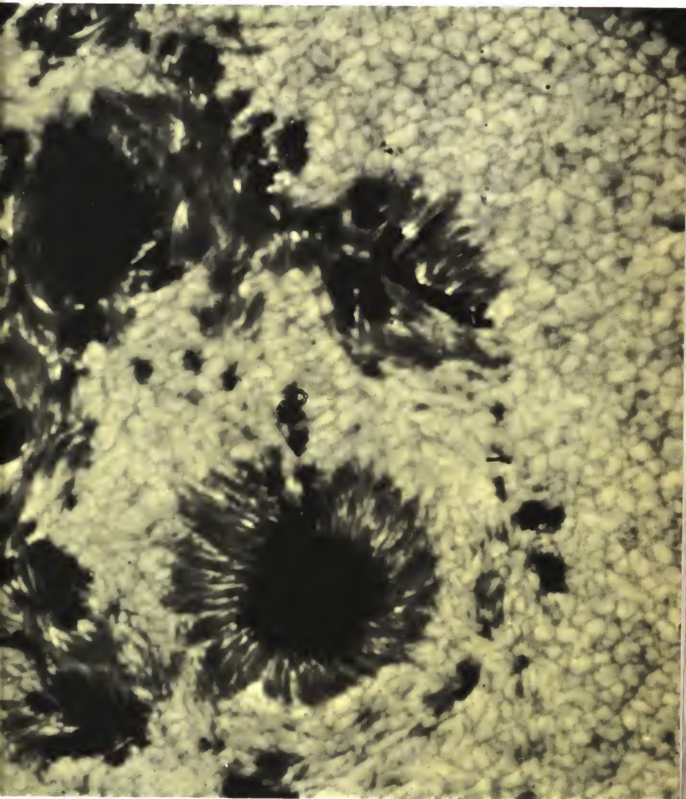
The reason for this is that the photosphere is a boiling mass of dense, hot gases. When pockets of gas deep within the photosphere become hotter than the surrounding gas they "boil up" to the surface, glow brightly for a while as they cool off, and then sink back to make way for other hot pockets that are rising up. It is this rising and sinking action that gives to the photosphere its typically rice-grained appearance.

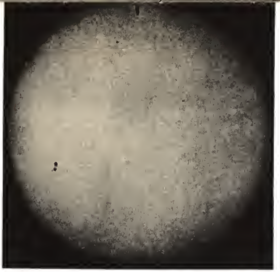
Although the photosphere is extremely bright to the eye, it is often marked with dark patches known as sunspots. Galileo and Christopher Scheiner began the first detailed study of sunspots very soon after the invention of the telescope in 1609. They noticed that the spots have a dark central area and a rim of a lighter shade. The "light" rim, however, is still darker than the bright surface of the surrounding photosphere. Later astronomers noticed something else about sunspots. Once every 11 years they increase in number from just a few to several hundred, and then decrease again.

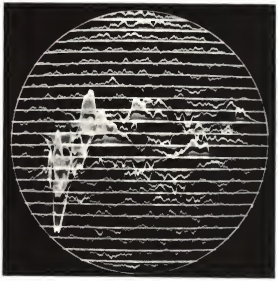
Although the study of sunspots has been going on for more than three and a half centuries, they were still something of a mystery until only 10 years or so ago; and even today astronomers still have much to learn about what causes them. Galileo was quick to realize that they demanded an explanation, for once they were seen, men had to begin thinking about the Sun in an entirely new way. The ancient Greeks had thought of the Sun as something unblemished and unchanging. But Galileo had seen the spots, or "blemishes," and he had noticed that they came and went, proving beyond doubt that the Sun is certainly not unchanging.

Various astronomers then tried to account for sunspots. Some believed that they were shadows and called the dark central portion the "umbra," meaning shadow or shade, and

Launched near Minneapolis in September 1957, this unmanned balloon rose 80,000 feet above the Earth, carrying a telescope equipped with a camera. At that height, where the air is thin, it obtained exceptionally clear photographs of the Sun's surface. The one opposite shows the rice-grain effect, caused by rising and falling pockets of hot gas, and also sunspots, one of which looks like a huge dark crater.







Sunspots look dark beside the bright photosphere around them, yet they emit light and are centers of magnetic activity. A photograph and a magnetic map of the Sun, both made on the same day, show magnetic activity to be strongest near the spots.

Every 11 years, sunspots first form far north and south of the Sun's equator. As their numbers grow they approach it, dying out before reaching it.

the light-colored rim the "penumbra," or part shadow. Others thought that the dark areas were high rocks rising out of a brightly lit sea and that the lighter rims were sandy shores; another theory was that the sunspots were volcanoes. All these ideas were wrong.

Today we know that sunspots are carried across the Sun's disk as the Sun rotates on its axis once every 25 days. When a spot nears one edge of the Sun's disk, or *limb*, it appears to become more and more "squashed up," or foreshortened. And as it passes around the edge of the disk we see it as a definite depression. These facts strongly hint that sunspots are hollows in the photosphere, whatever else they may be as well. If we watch the spots when they are in the central part of the Sun's disk we can learn something else interesting about them. We find that there is light and other radiation coming from even the darkest part of a spot. So sunspots are not really dark at all. They only appear dark in comparison with the intense brightness of the photosphere all around them.

We now know that sunspots are huge whirlpools of gas, with "roots" deep in the photosphere. Some astronomers believe that they are caused by a circulation of gases below the photosphere. This circulation, they say, travels with a kind of combined whirling and tunneling motion. Where the circulating material reaches the photosphere it bursts out in the form of spots—enormous hollows from which visible light and other forms of radiation pour out. With a radio telescope we can "hear" disturbances set up in the chromosphere just above a sunspot, and they are much more powerful than those normally sent out by "quiet" areas of the Sun.

Optical telescopes show that sunspots are closely linked with *prominences* and *solar flares*. Prominences are huge flame-shaped masses of hot gas, mostly hydrogen, that extend tens or hundreds of thousands of miles above the lower part of the chromosphere. The prominences are not flames, because flames are hot gases produced by the burning of other materials; there is no burning of this kind on the Sun. For some reason we do not yet fully understand, solar flares seem to

Solar prominences are masses of hot gas extending thousands of miles above the chromosphere. The pictures opposite were made in June 1946.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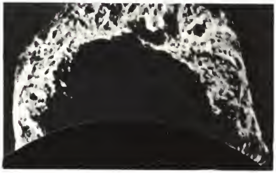
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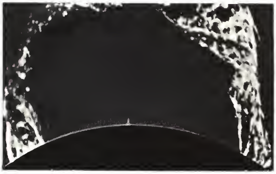
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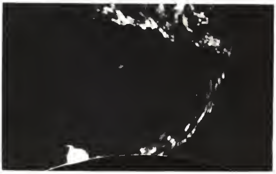
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occur when magnetic activity makes sudden changes around a sunspot. When this happens the energy produced by the magnetic activity in some way causes countless electrically charged particles to be shot out from the Sun.

The power generated by all this magnetic activity is enormous. We can get some idea of it from the effects it produces on the Earth. Sunspots, for instance, send out atomic particles that cause changes in the electrified layers of the upper air. Temperature changes follow high up in the atmosphere, and evidence is accumulating that as the number of sunspots alters rainfall is affected, and there are also changes in the winds.

Solar flares produce far more spectacular results. Many of the electrically charged particles that they hurl out are caught in the high layers of the Earth's atmosphere, where they travel back and forth between the North and South poles with almost the speed of light. In regions of the Arctic and Antarctic they give rise to the beautiful curtains of colored light that we call the northern lights and southern lights—the aurora; and over all parts of the Earth they cause electric "storms." By disturbing the layers of atmosphere that reflect short radio waves back to Earth—the layers called the *ionosphere*—they may also cause radio blackouts.

Whatever aspect of the Sun's appearance we think about—whether it is in a quiet mood or a particularly active mood—we cannot help being impressed with the colossal energy that lies within it. The photosphere itself, with a surface area of more than two million million square miles, is constantly radiating heat, light, radio, and other waves into space. While sunspots are associated with bursts of ultra-violet and other radiation, the prominences give out such heat that our hottest blast furnaces cannot begin to compare with them. And all this enormous output of energy has been going on for thousands of millions of years.

No ordinary chemical process, such as burning, can account for energy production on this scale. To find out how the Sun "keeps going" we must look for an explanation in

the atomic reactions that go on deep down in the interior, where the temperature may be as high as 20 million degrees. But how can we do this since we cannot see past the dense photosphere, which allows only a tiny fraction of the radiation below to pierce through? To discover just what atomic reactions go on inside the Sun we have to piece together three kinds of clues: (1) what kinds of atoms exist there; (2) how these atoms behave under varying conditions of heat and pressure; (3) what conditions of heat and pressure exist deep inside the Sun.

This piecing together of clues is an important part of *astrophysics*, the science concerning the chemical and physical nature of the universe. But before we can follow how the astrophysicist works, we must first look at some of the things that other scientists have learned about atoms.

The World of Atoms

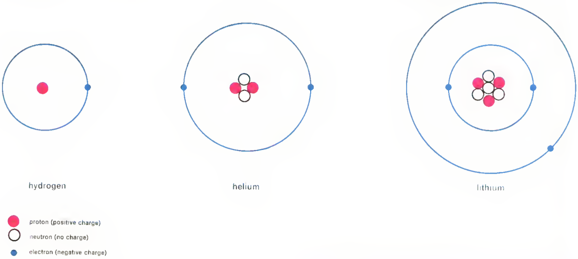
The atomic theory that the British scientist John Dalton put forward a century and a half ago made two main points. The first was that everything is made up of the smallest possible particles of matter, called atoms.. The second was that all the chemical elements differ in weight because they are made of different kinds of atoms: Very light elements, such as hydrogen and helium, are made of atoms that weigh very little, while heavy elements, such as mercury and lead, are made of heavy atoms.

This theory was extremely useful because it allowed scientists to explain many things in the world around them much better than they had been able to do before. In its broad outline Dalton's theory still stands good today. But as scientific experiments continued and new knowledge came to light, parts of the theory had to be discarded. In time it was clear that the atom is *not* the smallest possible particle of matter. In fact every atom is itself made up of a family of smaller particles, and some atoms are heavier than others because they contain more of these particles.

During our own century our knowledge of atoms has grown enormously. Chemists and physicists have found it useful to produce "blueprints" of atoms, which are drawn in the form of diagrams. These diagrams can be a great help to us so long as we remember that they are only diagrams, not pictures. Nobody has yet seen inside an atom and it is impossible to photograph one (although we can photograph certain things that they do). In spite of their shortcomings, these diagrams can give us a good working knowledge of what atoms contain and how they behave.

The radiation of the Sun and the stars is produced by atomic reactions, the atoms involved being the same as those on the Earth. These diagrams show the make-up of ordinary atoms of the three lightest elements.

We see opposite how a modern scientist pictures an atom of uranium, the heaviest of all atoms occurring naturally on Earth. In its heavy nucleus the Uranium-238 atom contains 92 protons and 146 neutrons.



To begin with, we can think of an atom as having a heavy central core, or *nucleus*, with a positive electric charge. Orbiting around the nucleus are one or more *electrons*, each having a negative electric charge. Within the nucleus are two different kinds of particles—*protons* and *neutrons*. Protons have a positive electric charge but neutrons have no charge at all. These three kinds of particles—electrons, protons, and neutrons—are the most important ones we need to know about, although more than a dozen other ones are now known.

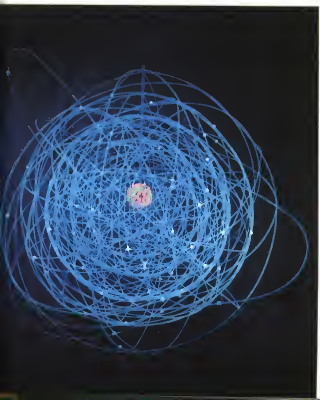
In every normal atom, the number of electrons is exactly equal to the number of protons in the nucleus. Since the protons carry a positive charge and the electrons a negative charge, this means that the normal atom is electrically neutral. But this is not the case with *all* atoms. Under extreme conditions of heat or pressure some electrons can be stripped away from the atom, leaving the atom with a positive charge.

The *chemical* difference between an atom of one element and an atom of another depends on the number of electrons and protons each contains. But since the number of electrons is normally the same as the number of protons, we need only think of the protons. Atoms of hydrogen have only one proton, atoms of helium have two, and atoms of lithium three. Uranium, with 92 protons, is the largest of all atoms that exist naturally on the Earth, but there are several larger ones that can be produced in laboratories.

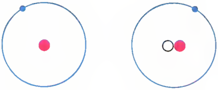
The difference in *weight* between one atom and another depends on the total number of protons and neutrons in the nucleus. The normal hydrogen atom, with only one proton and no neutrons, is the lightest of all. Next comes helium, with two protons and two neutrons, and then lithium, with three protons and four neutrons. The Uranium-238 atom, with 92 protons and 146 neutrons, is the heaviest of all.

So the chemical properties of an atom depend on the number of protons it contains, while its weight depends on the number of protons plus neutrons. Is it possible for two atoms to have the same chemical properties but different weights? The answer is yes.

Although the ordinary hydrogen atom has only one proton and no neutrons, a much rarer kind of hydrogen atom, called deuterium, has one proton plus one neutron. While both have the same chemical properties, deuterium is twice as heavy as normal hydrogen. Atoms that have the same number of protons but different numbers of neutrons are called *isotopes* of the same element.



The chemical properties of an atom depend on the number of protons it contains. Its weight depends on the combined number of protons and neutrons. These two atoms are chemically alike, but the deuterium atom (right) is twice as heavy as the hydrogen atom (left).



The fact that two atoms of the same element can differ in weight means that the nucleus of an atom can be changed. About 60 years ago the French scientists Pierre and Marie Curie discovered that changes of this kind are constantly occurring in radium. In a natural process of "decay," radium atoms give off particles and become lighter. Later work showed that similar changes occur in about 10 other heavy elements found in nature. Soon after World War I, Sir John Cockcroft and Ernest Walton succeeded in breaking down an atom by artificial means.

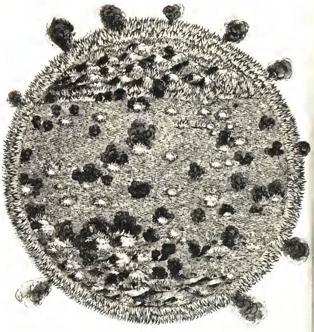
The nucleus of a heavy atom can be broken down by bombarding it with subatomic particles traveling at very high speeds. During this breakdown the original heavy atom becomes two atoms of a lighter substance. The two light atoms have almost exactly the same amount of matter as the original heavy atom—almost but not quite. Somewhere in the process—called *fission*—a tiny quantity of matter is lost. What happens is that some atomic particles cease to exist as matter and turn into radiant energy. This is how the explosive energy of the A-bomb is produced.

But there is another kind of process—*fusion*—in which the nuclei of two light atoms combine to form the nucleus of a heavier atom. In this process the light atoms are broken down and a single heavy nucleus is built up from them. Here, again, there is some matter "missing" after the reaction, and again the missing matter has been turned into radiant energy. It is this process that produces the tremendous power of the H-bomb—and that goes on deep inside the Sun.

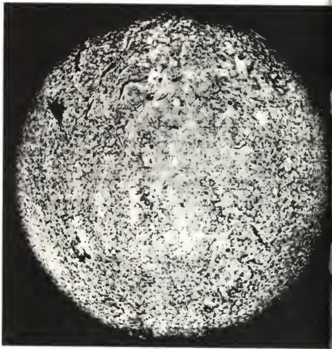
Rays that Travel Through Space

Everything we know about the Sun and the other stars we have learned from the various kinds of radiation that they give out—radio waves, heat, light, X rays, and so on; and all this radiation is produced by atoms. If we can discover just what connection there is between atoms and radiation we shall be much nearer to answering the question: What makes the stars shine?

All the forms of radiation mentioned above have two things in common: They all travel



This sketch of the Sun, made in 1635, hints at sunspots, corona, and solar flares, but it mainly suggests a huge ball of fire. The modern photograph, taken in hydrogen light, suggests the power of a vast thermonuclear reactor.



at the same speed—about 186,000 miles per second—and they are all affected by electric and magnetic fields, which is why they are referred to as *electromagnetic* radiation.

None of this radiation can be "seen" in the sense that the scientist can pick up and examine a piece of light, or put a radio wave under the microscope. But he can examine the effects of radiation—effects that we call light, radio waves, X rays, or whatever they may be. Some of his experiments show that radiation behaves as if it were made up of tiny particles too small to be seen. Other experiments show that radiation can also behave as if it were no more than a collection of waves. So it is best to think of all electromagnetic radiation as being made up of tiny particles of energy (called *quanta*), each of which acts like a "packet" of waves.

One kind of radiation differs from another only in the length of its waves. For instance, light waves and radio waves are both forms of electromagnetic radiation and both travel at the same speed. In addition, both have energy that can be used to do work: Light can be made to work a photoelectric cell, and radio waves can be made to excite the atoms in a radio antenna. The basic difference between them is that radio waves are millions of times longer than light waves.

The shortest waves we know of are *cosmic rays*. They are produced by cosmic-ray particles that rush into the Earth's atmosphere and bombard some of its atoms. We are not yet sure where all these high-speed cosmic-ray particles come from, but some are certainly hurled right away from the Sun. The wave length of the rays produced is less than .00 000 000 05 centimeter.

The next shortest are *gamma rays*, whose wave lengths vary between .00 000 000 05 cm. and .00 000 04 cm. They are generated deep inside the Sun and other stars and are sent out into space; but, like cosmic rays, they do not reach us on the Earth's surface because the atmosphere shields us from them. This is extremely fortunate, because very-short-wave radiation can do much damage to living tissue—and the shorter the wave length, the more damaging the radiation.

X rays, which may be as much as a thousand times longer than gamma rays, are also a danger to living tissue. When they were first used in hospitals more than 60 years ago, many pioneer workers suffered severe damage to their hands, arms, and faces because they did not realize that precautions had to be taken against X rays. Fortunately the Earth's atmosphere also shields us from these rays. Yet we know beyond any doubt that they are constantly given out by the Sun, because a short time ago an American rocket-borne camera succeeded in photographing the Sun using *only* its X radiation.

The Earth's atmosphere also keeps out a high proportion of the ultra-violet rays that would otherwise reach us from the Sun. These rays have a wave length of .00 000 1 cm. when they are at their shortest and .00 004 cm. at their longest. Only the longest and least dangerous of them can penetrate the atmosphere to the Earth's surface, but even these can cause what we call "sunburn," and too much exposure to them can be dangerous if we fail to take proper precautions.

Ultra-violet means simply "beyond violet," and when we come to slightly longer wave lengths, we begin to deal with rays that we can detect with our eyes. The shortest of these, with a wave length of about .00 004 cm., produce violet light. Next comes blue light (a little longer in wave length), then green (still longer), yellow, and finally red which is the longest of all the visible wave lengths, having a length up to .00 008 cm.

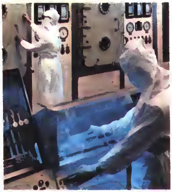
Beyond that figure we come to a vast range of wave lengths that are too long for our sight to register. Here we enter the region below the red, or the *infra-red*. Although we cannot see the infra-red rays from the Sun and the other stars, we can feel the shortest ones as heat. And when we come to the longest ones we are getting very near the beginning of the wave lengths that we can pick up with a radio receiver. The whole spread of radio wave lengths stretches from less than a millimeter to 2000 meters or more, but only a small part of them can penetrate the Earth's atmosphere. These are mainly the ones between $4\frac{1}{2}$ millimeters and 10 meters.

The Electromagnetic Spectrum

Cosmic radiation is the shortest known. It is emitted when cosmic-ray particles break up atoms in the air, as shown in this photograph taken at a high altitude.

Gamma rays, next shortest, mostly fail to reach us. Though harmful to living tissue they can be used in preserving. The gamma-irradiated potato (bottom) keeps extremely well.

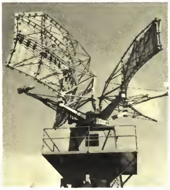
X rays too, fortunately for us, fail to penetrate the Earth's air belt. When this X-ray plate was made, over 60 years ago, radiographers often suffered injuries to hands and arms.



Ultra-violet rays, some of which reach the Earth's surface, are a little shorter than the rays that produce violet light. Here they are used to sterilize medicine containers.

Visible light is produced by rays ranging from about .00 004 to .00 008 cm. in wave length. This small part of the electromagnetic spectrum tells us most about the stars.

Infra-red rays have longer wave lengths than red light. By using photographic film sensitive to infra-red rays (right) we can take clear photographs in misty conditions.

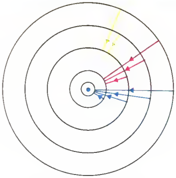


Radio waves have an enormous range of wave lengths. They can be as short as a few mm. or extend to thousands of meters. Radar makes use of the shortest radio waves.

Radio waves from the stars and galaxies can be detected by radio telescopes. Recently these instruments have added greatly to our knowledge of the universe.

The whole range of wave lengths emitted by the Sun and stars is known as the electromagnetic spectrum. Here, starting with cosmic rays and ending with short radio waves, we see how some of the different kinds of radiation are detected and used.

The entire spread of wave lengths from the shortest cosmic rays to the longest known radio waves, is called the *electromagnetic spectrum*. Within this spectrum lies all the radiant energy that atoms can give out or take in. Let us see, now, how this happens.



An electron can move around a nucleus in different orbits. In jumping from an outer to an inner orbit it emits radiation. The wave length emitted depends on the extent of the jump. Each atom has its own special range of jumps and so produces its own individual range of wave lengths.

Atoms and Radiation

We have already pictured an atom as being made up of a nucleus with a number of electrons orbiting around it, and we have seen that the hydrogen atom, the simplest of all, has only one electron. So long as we do nothing to add energy to the hydrogen atom, its electron will always keep to the same orbit around the nucleus. But the hydrogen electron (like all electrons) will respond to certain fixed wave lengths. So, if we add just the right amount of energy—that is, if we excite the atom with energy at the right wave length—the electron will jump outward to another orbit. When this happens the atom will absorb a certain amount of energy at a certain fixed wave length. A moment later, when the energy has been absorbed, the electron will fall inward to its original orbit. When this happens the atom will give out exactly the same amount of energy at exactly the same wave length.

The electron of the hydrogen atom can move in several distinct orbits around the nucleus, so it can make several different jumps. For instance, from orbit 1 it can jump to orbit 2, or to orbit 3, or to orbit 4; from orbit 2 it can jump to orbit 3, or to orbit 4, and so on. Each different outward jump absorbs waves of different length, while each different inward jump gives out waves of different length.

Since the electron can make only a limited number of different jumps, it follows that the hydrogen atom can absorb or give out only a limited number of different wave lengths. This turns out to be one of the most important clues that helps the astrophysicist to understand the inner workings of stars, and here is the reason: Hydrogen, helium, iron, nickel, chromium, calcium—every single element, in fact—each has its own particular range of wave lengths, *and no two ranges are exactly alike*. So if the astronomer can discover the pattern of wave lengths an atom gives out or absorbs, he can tell at once whether he is dealing with an atom of hydrogen, an atom of carbon, an atom of calcium, and so on.

The particular pattern of wave lengths that an atom gives out is called the *spectrum* of that atom. So astrophysicists talk about the spectrum of hydrogen, the spectrum of oxygen, or the spectrum of carbon. The spectrum identifies the atom just as certainly as your fingerprints identify you.

When a detective is lucky enough to find a clear set of fingerprints he can not only identify the person who left them but may also be able to discover something else about the person. For instance, if the prints reveal traces of dirt and oil, he may be able to deduce that the person had been working on a car engine. The astrophysicist can use the spectrum of atoms in a similar way. One kind of departure from the exact pattern he expects can tell him that the atoms are extremely hot; another kind of departure can tell him they are in a powerful magnetic field; and yet another kind can tell him whether the atoms are moving toward him or away from him. But how, you may wonder, is it possible for the astrophysicist to "fingerprint" atoms that are millions of miles away in space?

Here are the spectra of four different metals—copper, iron, nickel, and zinc. Each is quite different from all the rest. To the astrophysicist all are clear marks of identity, just as fingerprints are to a detective.

The Spectrum and the Stars

He cannot, of course, make use of all of the wave lengths of the electromagnetic spectrum. As we found earlier, the atmosphere blocks out the very short waves and the very long waves. So the astrophysicist has to depend mainly on the limited range of wave lengths that produce light, but he can also learn a lot from radio waves.

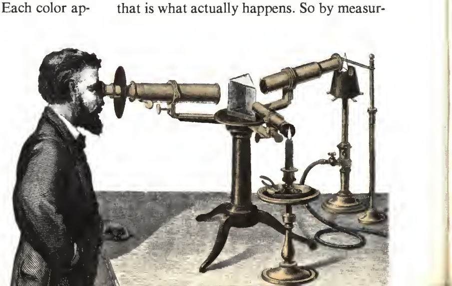
The light that comes from every star is produced by countless billions of atoms, some giving out one wave length and some another. So the astrophysicist needs an instrument that can split the light accurately into its many separate wave lengths, or colors. One way of doing this is by passing a star's light through a glass prism. But a single prism produces only a few separate colors, not really enough to provide all the clues we need.

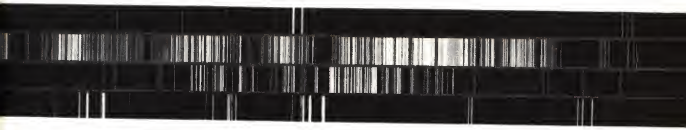
We must split the light into thousands of separate colors, or wave lengths, and to do that very special instruments are needed. Some of these, including the spectroscope and the spectrograph, are described later. For now, all we need to know is how these instruments are used and what they tell us.

When the light from a star reaches the eyepiece of a telescope, it passes through a fine slit before it reaches the instrument that splits it up into its separate colors. Each color appears as a thin straight line because each has been framed by the fine slit. From the astrophysicist's point of view, one of the most important things is that the line for every single color always falls in one particular place and no other. The complete set of lines—called the star's spectrum—can then be photographed and the exact positions of the lines measured. In this way the astrophysicist can tell just what kinds of atoms a star contains. He has learned by this method that the Sun and all the other stars we see shining in the sky are made up of precisely the same kinds of atoms as those we know on the Earth.

But the astrophysicist is not content to know only how many different kinds of atoms are present in a star. He also wants to know the proportions of one substance to another. For instance, if the spectral lines show that a star contains both hydrogen and oxygen, he wants to know which is more abundant, and by how much. He can find this out by measuring the intensity of the various lines. Let us suppose that there is 10 times as much hydrogen as oxygen in a star. We should then expect more radiation to come from the hydrogen atoms than from the oxygen atoms, which means that the hydrogen should produce more intense lines than the oxygen. And that is what actually happens. So by measur-

This picture comes from a book written some 90 years ago. It shows a simple spectroscope used for viewing the spectra produced by various substances in the laboratory. By attaching better models to telescopes, astronomers obtained the first spectra of the stars.





ing the intensity of the lines, the astrophysicist can say that hydrogen is 10 times more abundant than oxygen; but what he cannot tell by this method is just how many tons of hydrogen or oxygen the star contains.

Measuring the intensity of spectral lines has told astronomers a great deal about the make-up of the Sun and the other stars. They know, for instance, that the Sun contains 10 times as much hydrogen as helium. They also know that these two substances together are about a thousand times more abundant than the total quantity of all the other elements. Stars vary considerably in their make-up, but in a very high proportion of them hydrogen and helium are the main ingredients.

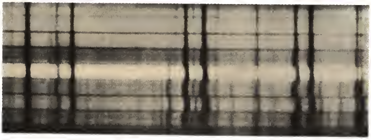
A star's spectrum can tell us even more about the star. By studying the many spectral lines under a microscope the astrophysicist can also discover the conditions under which the various atoms are giving out or absorbing energy. He can find whether the star's surface is very hot, whether it has a strong magnetic field around it, and whether the atoms are densely packed together or thinly spread out.

Let us see first what spectral lines can tell us about a star's temperature. If the surface of the star is very hot, some of the atoms at the surface will have lost one or more of their electrons; they will be *ionized*, as scientists say. And the higher the temperature, the more ionized atoms there will be. We can recognize the radiation from an ionized atom because some of its spectral lines are more intense than others. So if some of the lines are unusually bright, we can be fairly sure that the surface of the star is very hot.

But here we have to be very careful. Say that we are trying to learn something about two different stars of the same temperature. In one the atoms of gas are under high pressure, that is they are closely packed together; but in the other they are under low pressure—that is they are less densely packed. The fact is that there will be more ionized atoms in the gas under low pressure. This might lead us to think that spectral lines can do no more than tell us that atoms are *either* at a high temperature *or* at a low pressure, without enabling us to decide which.

Fortunately there is a way of deciding. Lines produced by ionized atoms under high pressure are slightly broader than those produced by ionized atoms under low pressure; also, their positions are slightly shifted. So with the help of very delicate instruments it is possible to measure the pressure at which ionized atoms exist. We can then sort effects of pressure from effects of temperature.

A human fingerprint not only identifies the man who made it. If it carries traces of oil or stain it may give a clue to the man's activities. Spectrum lines similarly offer clues to the conditions under which an atom is emitting radiation. These "split" lines indicate a magnetic field.



With the spectroheliograph, an instrument described in Chapter 3, it is possible to examine spectral lines from different layers of the Sun's atmosphere and discover what the temperature and pressure must be in each layer. That is how scientists can give facts and figures such as those we have seen.

A strong magnetic field produces an effect altogether different from high temperature or high pressure. Atoms in a strong magnetic field produce spectral lines that are split in the way shown in the illustration on the previous page. It was by detecting split spectral lines that astronomers first discovered the strong magnetic fields in sunspots.

Perhaps the most exciting of all the many things that spectral lines can tell us is whether a star or a galaxy is moving toward us or away from us. If you watch a balloon in the air you can tell easily whether it is moving toward you or away from you, because it seems to get smaller as it moves away, and bigger as it comes nearer. But the stars and galaxies are so very distant from us that we cannot possibly notice any change of size whichever way they move, even though they may be traveling at hundreds or even thousands of miles per second. Yet if we know how to read the secret of spectral lines, they tell us not only whether a galaxy is coming closer or moving away, but also the speed at which it is moving.

This is not difficult to understand if you remember what happens when a whistling train thunders past a crossing or through a station. As the train comes toward you the pitch of the whistle is high; but when it has passed and is moving away, the pitch falls, although the sound waves that the whistle gives out have the same wave length all the time. This is what happens:

As the train moves toward you the time delay between two wave crests reaching your ears is shortened, so that the wave lengths themselves seem shorter. With sound, shorter wave lengths mean a higher pitch, so you hear a more highly pitched note. When the train is moving away the time delay between the two wave crests reaching your ears is lengthened. Now the wave lengths seem longer, and so you hear a note of lower pitch.

Many people were puzzled by this change of pitch from a train whistle from the time of the first railways in the 1820s. Then in 1842 an Austrian scientist named Christian Doppler explained what caused it. At that time scientists already knew that light is also carried by waves, even though light waves are very different from sound waves. So they began to ask themselves whether a to-and-from motion can also affect the lengths of light waves, and Doppler and a French physicist, Hippolyte Fizeau, applied the idea to light. More than 60 years later, after many careful measurements, astronomers were at last sure that when a star or a galaxy is moving away from us the wave lengths of its radiation *do* seem to become longer; and this causes all its spectral lines to shift toward the long-wave, or red, end of the spectrum. For this reason, modern astronomers call this phenomenon the *red shift*. Because almost all galaxies—though not all the stars—we know of are moving away from us, their spectral lines are almost always shifted toward the red end of the spectrum, and not to the short-wave, or blue, end.

By carefully measuring how far the spectral lines are shifted away from their normal positions, astronomers can tell fairly accurately how fast a galaxy is moving away from

the Earth. The results of such measurements are astonishing. We find that many nearby galaxies are moving away from us at speeds of many hundred miles per second; and the most distant galaxies that can be seen in the largest telescopes are racing away at speeds of around 70,000 miles per second. This is nearly 40 per cent as fast as light. The farther away the galaxies are, the faster they seem to be moving away. This fact has led to several new and exciting theories about the origin and evolution of the universe, which we shall look at in a later chapter.

Piecing the Clues Together

We have seen that the astrophysicist has to piece together three kinds of clues in order to work out just what is going on inside the Sun and other stars. The most important clues are his knowledge of the different kinds of atoms that exist there, how those atoms behave under different conditions of temperature and pressure, and what he knows about the temperatures and pressures inside the stars. Now that we know how he gets most of these clues, let us see how he pieces them together and what he learns from them.

We can best begin as astronomers and astrophysicists themselves began—by asking questions about the Sun. How do we know, for instance, that the Sun definitely rotates and that sunspots are actually part of the photosphere—not just dark patches moving across the Sun's disk? The answer is that spectral lines from the western edge of the Sun show a red shift, indicating that that part of the Sun's disk is moving away from us; spectral lines from the eastern edge show a blue shift, indicating that that part is moving toward us.

This can mean only that the Sun is rotating on its axis; and by measuring the shift in the spectral lines we can work out the speed of rotation. It turns out that the Sun rotates more rapidly near its equator than near its two poles, the difference in time being about three days. The average speed of rotation for the whole body of the Sun is just over 25 days. Because we can actually see that sunspots are revolving in the same direction and at the same speed, we can conclude that they must be part of the Sun itself.

Again, how do we know that sunspots are centers of intense magnetic activity? Here we depend on the fact that spectral lines produced by light from sunspots are split, and this, as we have already seen, is a sure indication of a magnetic field.

A more difficult question to answer is: How do we know that the lowest layer of the Sun's atmosphere (the reversing layer) is cooler than the photosphere? Here we have to go back to what we know about how atoms give out and absorb radiation. When an electron falls from an outer orbit to an inner one it gives out radiation of a certain precise wave length; but when it makes a corresponding outward jump it absorbs radiation of exactly the same wave length. An inward fall, then, appears as bright lines in a spectrum while a jump outward produces dark lines in exactly the same positions.

Since the bright photosphere of the Sun is giving out radiation, we should expect to see bright lines all over the spectrum of sunlight, as we do in fact. The spectrum of sunlight shows a long succession of bright lines stretching from red to deep violet; but when we examine it closely we also find several dark lines crossing it. This must mean that

As a whistling train nears us we hear a high-pitched note. As it goes away we hear a note of lower pitch. By 1842 the reason was already understood. In the first case the sound waves seem to be shortened; in the second case they seem to be lengthened.

The same applies to a moving source of light. If it moves rapidly toward us the light waves seem to be shortened and the light looks bluer than it really is. If it moves rapidly away the waves seem lengthened and the light looks redder than it really is.

some of the radiation given out from the photosphere is being absorbed, and therefore never reaches us.

The next step is to find out how it is being absorbed, and here we can learn from experiments made in the laboratory. If we heat a lump of metal until it glows brightly it will produce spectral lines, just as the glowing Sun does. But if we then place a tube of cool gas between the glowing metal and the spectroscope, several dark lines appear on the spectrum; and each dark line corresponds to the wave lengths that the atoms of the gas can absorb. This laboratory experiment tells the astrophysicist that there must be a layer of cool gas just above the photosphere, and that this gas is what causes the dark lines in the Sun's spectrum. He calls this layer of gas the reversing layer simply because it reverses some of the bright spectral lines by making them appear dark.

This is by no means all that can be discovered about the reversing layer. We know that each kind of atom can emit or absorb radiation only at its own special wave lengths. We also know precisely which wave lengths are absorbed by the gas of the reversing layer. By combining these two pieces of information we can learn which elements go to make up the reversing layer. This is how we know that it consists mainly of hydrogen but also includes small quantities of certain other elements, including oxygen, titanium, and iron.

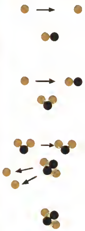
Problems of what goes on deep inside the Sun and the stars are more difficult, but we can solve at least some of them if we go on making the best use of all our clues. For instance, we have just seen that a glowing lump of hot metal will produce spectral lines, just as the Sun does. Can we take this to mean that the Sun is simply a hot, solid lump? Here the answer is a very firm no.

The more matter a heavenly body contains, the greater is the pull of gravity to its center. The Sun contains such a vast amount of matter compared with the Earth that the pull of gravity near its center is 100,000 million times greater than the pull of gravity near the surface of the Earth, and no solid substance could possibly stand the strain of this pull. If the Sun were made of *any* kind of ordinary solid or liquid, it would simply collapse of its own weight into a dense lump of material. The only explanation of why the Sun does not collapse is that the matter inside it is pushing outward with enough force to balance the inward pull of gravity. And the only kind of matter that can push outward with such great force is gas—but gas in a very special state.

Deep inside the Sun, the pressure and the temperature are so enormous that all the electrons are stripped away from the nucleus of each atom. These completely ionized atoms form a gas in which nuclei and electrons exist side by side but quite unconnected with each other. All of them are far more densely packed together than any atoms ever are on Earth—packed as people are in a city rather than in the country. Furthermore, they are all moving about, so that they are continuously colliding and producing reactions similar to those of a hydrogen bomb, but on a much greater scale. Only a very little of the colossal amount of radiation produced by these reactions deep within the Sun manages to break its way through to the surface. The rest of it exerts a tremendous outward pressure. It is just this outward *radiation pressure*, as it is called, combined with the pressure of the actual gases themselves, that prevents the Sun from collapsing inward.

When we say that only "a very little" of the radiation produced inside the Sun reaches the photosphere, what do we mean by "little"? The amount of energy given out by the photosphere in a single second is more than the total energy that human beings have used since man first lived on the Earth. Yet the Sun is a very ordinary sort of star, and there are millions of brighter ones in our own Galaxy. So the total amount of energy radiated by all the stars in the universe is utterly beyond our powers of imagination. And all of it is produced by atomic reactions.

Almost all these reactions produce heavier atoms (helium) that are built up by the fusion of lighter ones (hydrogen). The first stage occurs when two protons (that is, two nuclei



Two protons (hydrogen nuclei) collide, one becomes a neutron and they combine to form a heavy hydrogen nucleus.

Another proton joins this nucleus, which then becomes a nucleus of light helium.

Two nuclei of this kind collide and immediately throw out two protons.

What remains is a nucleus of ordinary helium like that shown on page 46.

The radiation of the Sun and the stars is produced by atomic reactions. The diagram shows one of the most important reactions that occurs in the Sun and other stars.

of ordinary hydrogen) collide. During the collision radiation is given off and the two protons combine, one of them becoming a neutron. The new neutron and the remaining proton together form the nucleus of a "heavy" hydrogen atom. The next stage follows when this nucleus of heavy hydrogen collides with another proton. During this second collision more radiation is given off and the nucleus of a light form of helium is formed. At the last stage two nuclei of this kind collide. They form one nucleus of ordinary helium and throw off two of ordinary hydrogen.

This is the simplest of all the reactions that take place in the Sun and most other stars. In somewhat hotter stars there is another very important reaction in which nuclei of carbon and hydrogen go through many series of collisions and eventually produce carbon and helium. And when we come to still hotter stars there are some other complicated reactions that give rise to atoms heavier than helium. The kinds of reactions that take place in a star depend mainly on the temperature.

Stars vary widely in brightness, which means that they also vary widely in temperature. By examining the spectra of many different stars, the astrophysicist can compare brighter ones with dimmer ones, discover what reactions go on inside each, and learn whether there is any kind of relationship between them. Here one of the clues the scientist looks for is color, since he knows that a very hot lump of iron, for example, glows with a bluish-white light, while a cooler one glows with a red light.

In the very bright stars, the most intense radiation from the surface is found in the blue part of the spectrum. Most of the spectral lines of these bright stars are due to atoms that ionize only at high temperatures—such as helium, oxygen, and nitrogen. This means that the very bright stars must also have very hot surfaces. As we pass to stars that shine less brightly, we find that their most intense radiation is not so close to the blue end of the spectrum. Their strongest spectral lines are those caused by the atoms of elements that ionize at a lower temperature, such as iron. From dimmer stars, like the Sun, less energy is being given out. Here the metal atoms are not even ionized, and the most intense radiation comes from nearer the red end of the spectrum. In stars that are still less bright, many of the lines show that some of the atoms are linked together as *molecules*. This means that these stars may contain chemical compounds, such as titanium oxide, which is a compound of titanium and oxygen. The presence of molecules also means that such stars are rather cool, with their main radiation at the red end of the spectrum.

Classifying all of these different types of stars by their spectra has not been easy and has taken many years of trial and error. Today astronomers use the following sequence of letters of the alphabet to classify the stars: The brightest and hottest stars are called O stars. Next come the B stars, which are neither quite so bright nor quite so hot. Then follow A, F, G, K, and M stars, in that order, the M stars being the least bright and the coolest. This *spectral sequence*, as it is called, is very important, as we shall see in a later chapter when we consider the birth, life, and death of stars. So it is worth trying to remember the correct order. An easy way of doing this is to think of the sentence: **Oh, Be A Fine Girl and Kiss Me.**

3 The Astronomer's Tools

Today we know that the planet Jupiter has an atmosphere made up mostly of hydrogen, although it contains some ammonia and methane as well. The spectacular rings of Saturn are made of millions upon millions of tiny "moonlets" too small to be seen individually even in the largest telescopes. We also know that the temperature on the planet Uranus is something like –190°c. With instruments undreamed of only a hundred years ago astronomers can find the distances of the stars by measuring angles so small that the width of a pin held half a mile away from the telescope would make a comparatively large angle.

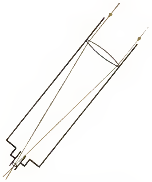
Considering that the planets and stars are seen only as tiny specks in the night sky, how is it possible for the astronomer to measure their distances as he does? And how can the astrophysicist be reasonably sure about the temperatures of the planets and the composition of their atmospheres? The answer lies in the special tools and equipment which the astronomer and astrophysicist have devised.

The earliest astronomers used their eyes and simple instruments like the quadrant to measure angles, but 350 years ago, in 1609, Galileo turned his homemade "optik tube" or telescope to the heavens and astronomy entered a new era. Since that time the astrophysicist has learned to apply photography and electricity to his problems, to split up sunlight and starlight and analyze it, and to make many uses of other radiation that reaches us from deep space.

Radiation from the heavens is, in fact, the only source of information from which astronomers can build up a picture of the universe. This radiation reaches us in three forms—light, heat, and radio waves. We observe and measure light and heat with optical telescopes, and radio waves with radio telescopes.

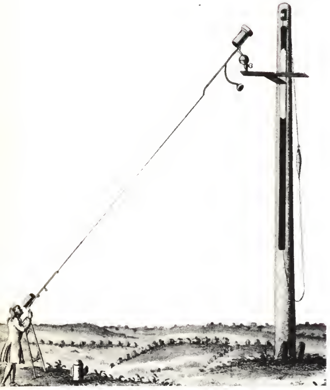
The two main kinds of optical telescope are the refractor and the reflector. Both collect light from distant objects and bring it to a focus so that a small picture—the *image*—is formed. In both instruments the image is then magnified by an eyepiece.

For thousands of years men saw only the stars visible to the naked eye. In the early 17th century telescopes first enabled astronomers to see satellites of planets and many new stars. Helvelius, above, had a telescope 12 feet long that magnified things 50 times. Today, with radio telescopes like that at Jodrell Bank, we can "hear" far distant galaxies.



This is how the first simple refracting telescopes worked. A big lens (the object glass) collected light from a star and bent it toward the focus, thus forming a small image. This was enlarged by the eyepiece.

Very long refractors raised a serious problem. On windy nights the tube bent, causing errors of observation. Some 300 years ago Christian Huygens avoided this by using an "aerial telescope" with object glass and eyepiece kept in line by a tight string.

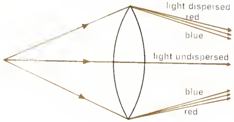


Refracting Telescopes

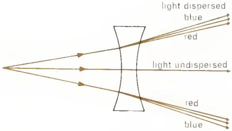
The kind of telescope most of us are familiar with is the refractor with a large lens at the front end. This front lens, called an *object glass* because it faces the object being observed, collects the light and bends or *refracts* it toward the focus. This principle sounds simple enough, but to put it into practice is not always easy. The reason is that no one has yet designed a lens that can bend light rays of all colors by the same amount. Violet and blue light are bent most and red light least. So if we use only one lens as the object glass of a refracting telescope it brings the rays of different colors to focus at different points, and we see an image surrounded by a hazy colored edge. In the early days of the telescope, astronomers found this a great nuisance when they were trying to make accurate observations and measurements. However, in 1733 an Englishman named Chester Moor Hall, who studied the optics of the eye as a hobby, found a way of overcoming this difficulty. Later, John Dollond made lenses based on Hall's idea.

The solution that Hall found was to use two lenses, one made of denser (more compact) glass than the other. The first lens is designed to bend the rays more strongly toward the focus than necessary. The second one works the opposite way by bending the rays slightly away from the focus. Together the two lenses act in such a way that the rays are brought gradually toward the focus. But how does this use of two lenses prevent the formation of colored edges round the image? The answer is that when light is refracted by a lens made of dense glass, the different colors are more widely spread out than they are when refracted by a lens made of less dense glass. As the illustrations show, in a two-lens object glass the light is first refracted strongly toward the focus and the colors dispersed a certain amount; then it is refracted a little away from the focus by a lens of different shape, and the dense glass of the second lens causes the colors to combine again.

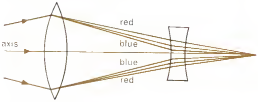
A double lens of this sort is called *achromatic*—that is, "no-color-edge." But this name is really a little optimistic, since



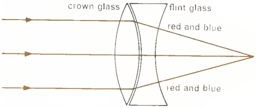
Another drawback was that the object glass split up the light, bending blue rays more than red ones. This caused a color blur around the image.



A concave lens bends light away from a focus, refracting blue light more than red light.



By combining a convex lens that refracts light strongly toward a focus with a concave lens that refracts it away, the colors are brought together.



If we use lenses of different glass we can do the same but avoid wide spacing.

Achromatic or no-color-edge lenses must be made of perfect glass, and this means that they are seldom large. The biggest of all, in this refractor at Yerkes Observatory, Wisconsin, U.S.A., has a diameter of 40 inches.

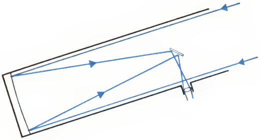
no two lenses can bring *all* of the colors back together again perfectly. In fact, they can do so only for two colors. So achromatic refracting telescopes are made either to bring the yellow and green rays together or to bring the blue and green rays together. By bringing together yellow and green, we get a sharp image for the two colors to which the eye is most sensitive. By bringing together blue and green we get a sharp image for the colors to which ordinary photographic materials are most sensitive.

Reflecting Telescopes

There is another way of solving this problem of colored edges. If we gather light by using a curved mirror instead of an object glass, we can do away entirely with the difficulties caused by lenses. The curved mirror will bring all the colors to the same focus, and even though we still have to use an eyepiece made of lenses, it is possible to design the eyepiece in such a way that it does not produce any unwanted color effects. So in this respect, at least, the reflecting telescope with its big curved mirror is better than the refracting telescope with its big lenses. And if we look still further into the matter we find that this is not the only advantage that the reflector has.

One of the greatest advantages is that reflecting telescopes can be made very much bigger than refractors; and the bigger we make a telescope the more light we are able to collect with it. This is tremendously important to the astronomer because as he explores farther and farther into the heavens the stars and galaxies he observes become dimmer and dimmer. It is equally important to the astrophysicist, who wants to gather as much light as he can so that he still has something bright enough to photograph even when he has spread the light out into a spectrum.

What decides the "light-grasping" power of a telescope is the area of its object glass or its mirror. It is just in this matter of area that the reflector scores over the refractor. In a refractor the light must first pass through the lenses of the object glass. If it is to do so



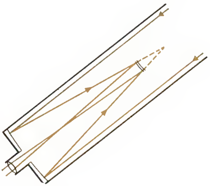
In the time of Isaac Newton there were no achromatic lenses. To beat the color-blur problem he made a telescope that used a curved mirror instead of a lens. The curved mirror focused the light from a star toward a tilted flat mirror. This carried the star image to an eyepiece at the side.

Large mirrors are less hard to make than large lenses. This is why the biggest telescope in the world, the Hale telescope at Mount Palomar Observatory in California, is a reflector. Its mirror, 200 inches across, can collect about 25 times as much light as the 40-inch lens of the Yerkes refractor.

without distortion those lenses must be free from blemishes—air bubbles, scratches, and strains—and they must be of precisely the same density throughout. This perfection is difficult to achieve even in a fairly small lens, and as the area of an object glass increases the task becomes more and more difficult until eventually it is technically impossible.

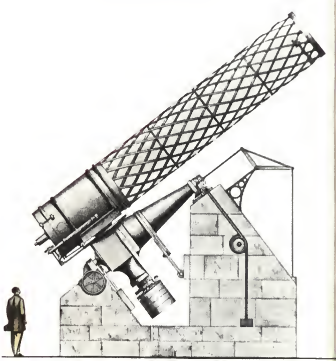
With the reflector the problem is not nearly so difficult. Light does not have to pass *through* the curved mirror; it is merely reflected from a highly polished thin film of aluminum spread over the surface of the glass. So long as the glass is strong enough it does not matter if there are a few bubbles in it or whether it is of exactly the same density throughout. It has only to be free from strains, which can be avoided by careful cooling of the mirror after it is cast. This does not mean that making a really large mirror is easy, but it is certainly far less difficult than trying to make a lens of the same size. This explains why the largest refracting telescope in the world, which is at Yerkes Observatory, Wisconsin, has an object glass of 40-inch diameter, while the largest reflector, which is at Mount Palomar in California, has a main mirror of 200-inch diameter. The cooling of this mirror, by the way, took nearly a year and a half. So the world's largest mirror has a diameter five times greater than the world's largest lens. This means that it has an *area* 25 times greater, which gives it 25 times as much light-grasping power.

The sheer size of a telescope lens or mirror is important for still another reason. We can understand why if we stop to think what happens when we look at, say, two golf balls lying about an inch apart on a golf course. If we stand only a few yards away we can see both balls distinctly. But when we move six hundred yards or so away we can see only a vaguely defined white blob, and we can no longer be sure whether we are looking at one ball or two. From that distance the angle between them is so small that the lens of the eye cannot separate or *resolve* them. But if we use a telescope equipped with a lens bigger than the lens of the eye, we can once



Cassegrain, a French astronomer who lived at the same time as Newton, designed another kind of reflector. The main curved mirror reflected light onto a small mirror curved the other way. Light from the small mirror was reflected back to a hole in the main mirror.

Cassegrain's design was not favored in his own time, but by 1860, when very big instruments were made, his invention proved most useful, allowing observers to work safely at ground level.

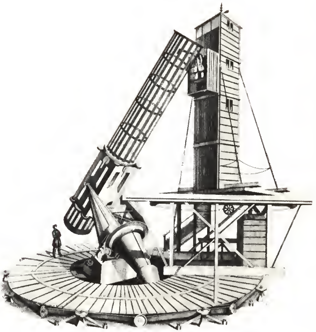


more see the two balls quite distinctly. The bigger the lens or the mirror of a telescope the greater is its resolving power. So with the giant reflector at Mount Palomar an observer can see hundreds of distinct stars in an area of sky where a small telescope might reveal only a hazy patch of light.

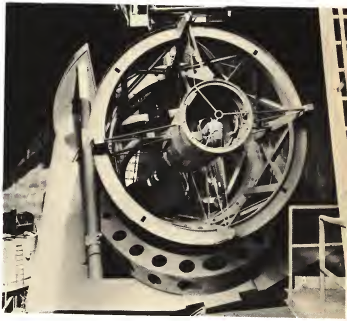
The main mirror of a reflecting telescope brings the light from a star to a focus and produces a small image. The light from this image now has to be reflected a second time so that the rays can be brought to an eyepiece or a camera; and the eyepiece or camera must be placed out of the way so that the light coming from the star to the main mirror is not interfered with. (There are exceptions to this rule. The Hale 200-inch reflector and the 120-inch reflector at Lick Observatory are so big that an observer can sit in a small chamber inside them without blotting out too much of the light.)

There are several ways of bringing the light from the image to the eyepiece or camera, but only two are now commonly used. In the kind of telescope invented by Isaac Newton, and known as the Newtonian reflector, the light is turned through a right angle and brought out to the side of the telescope tube by a small flat mirror tilted at an angle of 45 degrees. In the Cassegrain telescope, named after the French astronomer who invented it, the light from the image is reflected by a small convex mirror straight back to a hole cut through the center of the main mirror. This second method has certain advantages in some observations, but not in all. Many reflectors made nowadays therefore have a system by which the small mirrors can be changed, so that the telescope can be used either as a Cassegrain or as a Newtonian reflector. In some of the larger reflectors the small mirrors can be replaced by a plateholder which does away with the need for a second mirror, and so enables all the light that is gathered to be used for taking special photographs—of dim objects, for example.

It is not only the difficulty of making large refractors that causes astronomers to prefer the reflector. Another point against the refractor is that lenses reflect away a little light



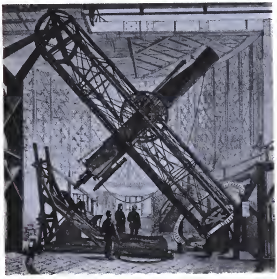
This Newtonian reflector, used in Malta a century ago, was less convenient than the Cassegrain. Observers needed a high tower to reach the eyepiece. As the telescope followed the track of a star across the sky, the tower was moved around on rails.



The Hale telescope can be used in Cassegrain's way but not in Newton's. It is also possible for an observer to sit inside it.

By making a time exposure with the camera pointed to the north celestial pole, we see how stars trace out circular arcs in the sky each night.

Here is an equatorial mounting formerly used at Greenwich in England. In spite of the Earth's rotation it always points to the north celestial pole, while the telescope is trained on a star. A mechanical drive turns it to follow the star's track.



at each of their surfaces. The big ones used in an object glass also absorb some of the light that is passing through them. In this way some of the precious light gathered by the telescope is wasted. Because every lens "loses" a certain amount of light astronomers like to use as few as possible, even in the telescope eyepiece. They have therefore dispensed with the lens in the eyepiece that is required to make distant objects appear the right way up. This is why astronomical telescopes show everything upside down.

A telescope—even a small one—is of little use unless it is mounted on a strong, rigid stand. On the other hand, the astronomer must be free to point it to any part of the sky and also to use it in following the stars in their journey across the heavens. The Earth's rotation makes the stars appear to follow circular paths around the north and south celestial poles. So what the astronomer needs is a mounting that will allow his telescope to follow these circular paths by one simple motion. This problem was solved many years ago when the *equatorial mounting* was designed. The telescope is mounted in such a way that it can be turned around a fixed line—called the *polar axis*—which points toward the celestial pole all night long, in spite of the Earth's rotation. It can also be pointed toward a particular star by turning it around a second axis at right angles to the polar axis. Once the telescope has been trained on a star an automatic drive takes over and keeps it rotating about the polar axis so that it automatically follows the motion of the chosen star. Equatorial mountings are fitted to every large professional telescope and they are used by many amateur astronomers as well.

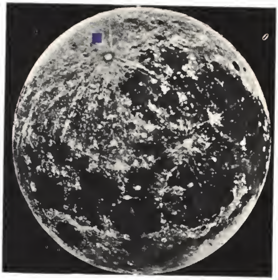
Photographing the Heavens

In professional observatories almost all observations are now made with the help of cameras, but there is one important exception —the measurement of certain "fundamental" star positions. Most stars have their positions determined from photographs that show the position of one star in relation to others. But before these relative positions can be of any

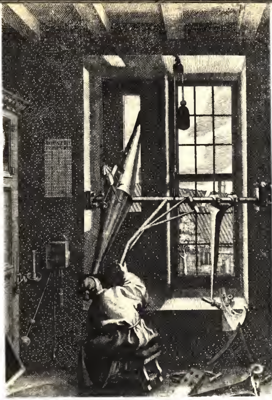
use, the absolute positions of some "fundamental" stars must be found, to serve as first reference points for all the other measurements. It is here that direct visual observation comes in.

Using a small refractor fixed as accurately as possible in a north-south direction, the astronomer carefully times the movement of a star across the sky, marking the precise moment when it crosses each of a number of fine vertical wires fixed in the telescope eyepiece. At the instant when the star is due south of him (or due north if he is working in the Southern Hemisphere) he must measure the angle it makes with the horizon. Then, because he also knows the exact time of his observation and the exact position of his observatory, he can fix the absolute position of the star with great accuracy. All this is done with an instrument known as a *meridian circle*. The fundamental stars whose positions are measured in this way can then act as reference points on photographs that record the positions of other stars.

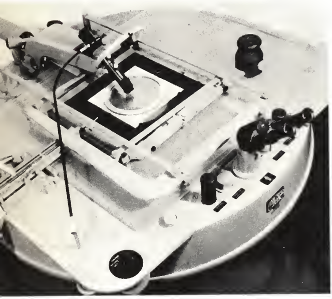
The first photographs used in astronomy



Astronomers first made use of photography over a century ago. Above is the Moon as a camera of 1857 saw it. Better equipment now sees it in far more detail. The photograph below was taken with the 200-inch Hale telescope.



Measuring star positions while at the telescope is not easy. Three centuries ago Olaus Römer, above, used special equipment to cut errors to a sixtieth of a degree. Today star photographs can be accurately measured with a plate-measuring microscope such as that shown below.



were of the Sun, taken by the French scientists Léon Foucault and Hippolyte Fizeau in 1845. The first successful Moon photographs were taken five years later by the American astronomer George P. Bond. By using highly sensitive film or plates astronomers today can photograph stars much too faint to be seen even in the largest telescopes. Such photographs can show more than the eye can ever see because a photographic film or plate can build up a picture over a long period through a time exposure, whereas the eye cannot. If we look at something just too dim to be seen, no matter how long we stare at it we cannot see it. On the other hand, we can take a photograph of it if we expose the film for a long enough time.

Another important advantage of photography is that it provides astronomers with permanent records from which accurate measurements can be made. To make measurements when looking through a telescope is not easy, and they can be only as accurate as our eyes will permit. With a photograph, however, the situation is very different. The plate can be examined under a microscope and distances on it can be measured to within a thousandth of a millimeter. On some plates this is equivalent to measuring the part of the sky that a golf ball would take up if it were 500 miles away! The instrument used for this precise work is known as a *plate-measuring microscope*.

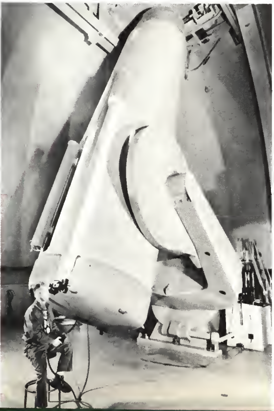
By carefully measuring star photographs in this way, astronomers can not only plot the exact positions of stars, they can also find out how far away they are. The method is fairly simple. If we know the length of one side of a triangle and can also measure two of its angles, we can work out the lengths of the other two sides. Surveyors do the same thing when they sight a high mountain peak from two different points a known distance apart. The two chosen points and the mountain peak form the three corners of a triangle. The surveyor knows the length of one side and he can easily measure the angle from each of its two ends to the mountain peak. He can then work out how far away the mountain peak is.

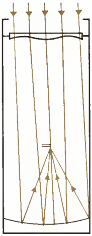
But even the nearest star is so far away that it is useless to try sighting it from two points (New York and Tokyo, for instance) at a measured distance apart on our own small Earth. If we did so we would find that the difference in the angles from each point to the star would be so small that we could not possibly measure it. What is needed is a base line far longer than any distance that can be found on the Earth's surface. To find such a distance we must make use of the Earth's predictable positions as it moves in its orbit about the Sun.

The astronomer solves this problem by taking one set of photographs at one time of the year and another set exactly six months later when the Earth is at the other side of its orbit, as we saw in our diagram on page 36. He then knows that two points of his triangle (his base line) are 186 million miles apart, which is the diameter of the Earth's orbit. By using this long base line and measuring very small angles he can determine how his chosen star seems to have shifted against the background of more distant stars. In this way he can measure distances as great as about 325 light-years, or more than 20 million times the Sun's distance from us. Because this method of measurement involves the apparent shift of one star against the background of more distant stars, it is known as a *parallax* measurement, from a Greek word meaning "change." This method will not work for stars that are more than 325 light-years away because the angles then become too small to measure.

The camera used in most types of astronomical work consists of a light-tight box, made to hold a photographic plate, fixed to the eyepiece end of a reflecting telescope. This system works quite well when photographs of small areas of the sky are wanted—say close-ups of the surface of the Moon, pictures of the planets, or more especially, photographs of galaxies. But there are times when the astronomer wants to photograph a large area of the sky in a single exposure. This can happen when he is making a photographic map of the stars or photographing a comet with a long tail. For this kind of work the ordinary reflecting telescope is not suitable, since it does not give wide enough coverage of the sky. In any ordinary reflecting telescope the stars near the edge of the field of view appear fuzzy with little tails, a defect caused by the shape of the curved mirror.

In 1930, to overcome this problem, the German astronomer Bernhard Schmidt built a new instrument. Schmidt used a mirror with a simpler curve than that used in ordin-



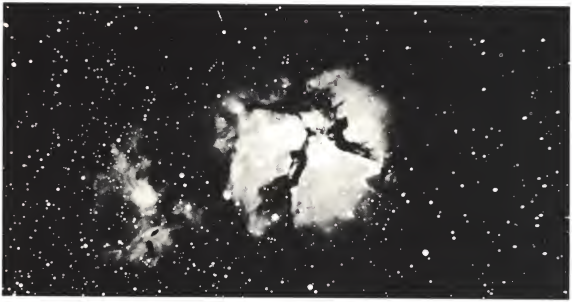


An especially useful instrument for photographing large areas of the sky in a single exposure is the Schmidt camera. The one shown here is the largest in the world, used at Mount Palomar. Its main features, shown in the diagram, are a mirror of simple shape and a correcting plate to eliminate distortions that the mirror would otherwise produce on the photographic plate.

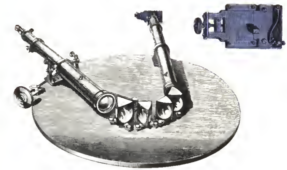
ary telescope mirrors. This simple curve gave a very wide field of view, but, in doing so, it distorted the star images in various other ways. What Schmidt did next was to place a specially shaped glass plate in front of the mirror to correct these errors. This *correcting plate* is very nearly flat and it does not produce a noticeable color blur around the edge of the image as an ordinary lens does. The photographic plate is placed between the correcting plate and the mirror. The whole instrument, known as a Schmidt camera, not only takes excellent pictures of large areas of sky but also acts as a very fast camera lens, so that quite short exposures can be made. One of the largest of the Schmidt cameras now in use is the famous 48-inch at Mount Palomar. This telescope and the other Schmidts in use have helped astronomers discover many *novae* or "new stars."

Astronomical photography seldom stands still for long, and experiments are now being made with other special types of camera. One method is to use a very sensitive television camera at the eyepiece end of the telescope and then to transfer the resulting picture to a television screen. By doing this and getting a bright television picture very short exposures—like those in ordinary photography—can be made. This means that the astronomer can make real use of those odd fractions of a second when the air is steady and make a photograph at just such a moment. Good pictures of the planets are at last in sight. Already photographs of the Moon show the great improvements possible as compared with ordinary photographs through the same instrument. In time the television camera may also make it possible to record stars that are too dim to show up on ordinary photographs.

Another photographic method that scientists are working on, especially in France, uses a device called the electron camera, which was invented by André Lallemand. In this camera light from the telescope falls on a piece of metal foil that reacts in a special way. From every part of its surface receiving light electrons are emitted—many where the light is intense, few where the light is dim. The electrons are guided on to a photographic plate that they act on in a way similar to light, so producting a photograph. This new instrument is so sensitive that it can photograph star spectra that are spread out widely, thus revealing fine detail. A recent spectrum of a type of red star, produced with the help of the electron camera, has shown the existence of molecules of titanium oxide more clearly than ever before.

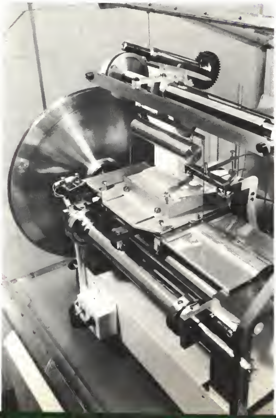


This photograph, taken with the Schmidt camera pictured on the previous page, shows the Trifid Nebula in Sagittarius.



This 19th-century spectroscope used four prisms to spread out spectrum lines as widely as possible. With instruments like this astronomers made the first good maps of the Sun's spectrum. The all-important slit is shown separately.

Some spectroscopes use a grating instead of prisms. To make a grating we must rule many fine lines on a hard surface. This machine can rule 28,800 lines to the inch.



"Fingerprinting" the Stars

Photographing the spectra of stars is an extremely difficult and complicated business. To begin with, no spectrum can be photographed unless the incoming light from the star is split up into its separate colors and spread out into a band. To do this we need a *spectroscope*, and there are two different kinds. One has a glass prism that splits up the light; the other uses a grating to accomplish the same thing.

The prism spectroscope, which is the more common of the two, contains a triangular block of glass that disperses the light entering it so that the rays of different colors are bent through different angles. The light is first passed through a narrow slit then through a lens to align the light rays all parallel, and after that to the triangular-shaped piece of glass—the prism. After being spread out by the prism, the light is then examined with a small telescope. When the astrophysicist wants the colors spread out more than one prism alone can do, he uses a spectroscope with two or three prisms. But since each prism absorbs some of the light that reaches it, there is less and less light left for forming a spectrum. So a spectroscope of this kind can be used only for examining the brighter heavenly bodies.

The second form of spectroscope uses a grating to spread the light into its various wave lengths. A grating consists of a number of fine lines ruled very close together on a piece of glass. The spacing between one line and another is about one thirty-thousandth of an inch. As light passes through this grating it is spread out in different directions, just as the waves of the sea are spread out in different directions when they pass through holes in a breakwater. The direction in which the light waves are turned depends on the wave length, and so the grating, like a prism, disperses light into its separate colors. The piece of glass on which the lines of a grating are ruled does not have to be transparent so that light passes through it. The method works just as well if the lines are ruled on to a highly polished aluminum surface from which the light is reflected.

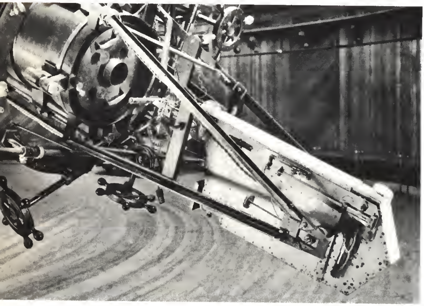
Strictly speaking, the spectroscope is an instrument that is simply used to split up light and spread it out into a set of spectrum lines. The instrument that also enables us to photograph the spectrum is called a *spectrograph*. In a spectrograph a camera is used instead of the small viewing telescope of an ordinary spectroscope.

As we saw earlier, light passes through a slit on its way from the telescope to the prism or grating. This is nearly always necessary because in the telescope the images of stars appear not as precise points of light but spread out into tiny patches. If a slit were not used, the spectral lines could not be very clearly seen and it would be difficult to measure their precise positions. The slit, then, is of great importance and it has to be a piece of precision equipment. On each side it has two steel "jaws" beveled at the edge and free to move toward or away from each other. The movement of the jaws is controlled by a screw, so that the slit can be adjusted according to the brightness of the star being observed. By using slit spectrographs astrophysicists have discovered that hydrogen is the most abundant element in the universe. They have also found out that the stars have magnetic and electric fields; also that there is water vapor and carbon dioxide in Venus's clouds, and that there is hydrogen, ammonia, and methane in the atmosphere of Jupiter.

When astronomers make detailed studies of the Sun or the other stars they always use a slit spectrograph. But if they want to measure the precise positions and widths of the spectral lines, merely photographing the spectrum is not enough. Unless they know exactly where the spectral lines *should* fall, they have no way of telling whether or not the lines are shifted—say by the red-shift effect described earlier. What is needed is some kind of standard with which they can compare the spectrum being studied.

We have such a standard if we photograph the spectrum of some well-known chemical element through the spectrograph. This *comparison spectrum* is usually the spectrum of iron. The reason iron is chosen is that it produces spectral lines throughout the whole range of visible light. One photograph of the iron spectrum is taken before the star spectrum is photographed, then another is taken afterward. This means that any changes in the spectrograph itself—due to the cold night air, for example—are taken care of.

When all this is done we have a photographic plate with three spectra on it, one above the other. At the top is the first comparison spectrum of iron, in the middle is

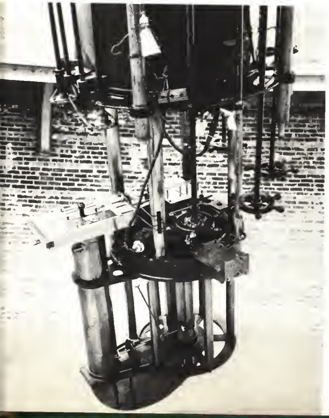


On the left is a spectrograph (the optical parts of which are in the white case) attached to a 36-inch refractor. It is used for photographing the spectra of stars. On the right, attached to the 40-inch Yerkes refractor, is a spectroheliograph. This has been used to obtain the spectra of many flocculi (small cloudlike forms that dot the Sun's surface). The results have added to our knowledge of how the Sun rotates.

the spectrum of the star, and at the bottom is the second comparison spectrum of iron.

Our *spectrogram,* or spectrum photograph, now has to be measured with the help of a measuring microscope. Accurate measurements of spectral lines have brought the astrophysicist amazing results. By checking their position and whether they have shifted to the red or blue end of the spectrum, he can tell how the Sun is moving in space and how distant islands of stars and gas are speeding out into the depths of the universe at hundreds and even thousands of miles per second. Without spectral lines and the ability to measure their positions accurately on photographs none of this knowledge would be ours.

When astronomers take spectrograms of the Sun they never have difficulty in obtaining enough light. More often the problem is to exclude some of the light, and for this purpose devices other than straightforward spectrographs may be used. One of the most important of these is the *spectroheliograph,* invented by the American astronomer George Hale, the man who was mainly responsible for the construction of the 200-inch telescope. The purpose of the spectroheliograph is to take photographs of the Sun in light of one particular wave length only. Photographs of



this kind make it possible to study how a particular gas or other substance is behaving over the whole of the Sun's surface.

The spectroheliograph is really a two-slit spectrograph. The main part of it consists of a slit, lens, prism, and camera—just as in the ordinary spectrograph. But there is also a second slit placed just in front of the photographic plate. This second slit allows the light of only one particular spectral line to fall on the plate. Just before the photograph is taken, the image of the Sun is carefully focused so that only the light from the edge of one limb falls on the first slit. A spectrum is formed and then one chosen line of it is isolated by the second slit. Next, while the photographic plate is being exposed, the two slits are moved. In this way the front one gradually scans the whole of the Sun's disk while the second one continues to isolate the single chosen line.

The result is that an image of the Sun at only one selected wave length is built up on the photograph. The spectroheliograph makes it possible for astrophysicists to take a photograph of the Sun showing how hydrogen is spread over the photosphere or to see how calcium, for example, is spread out just below it. This allows them to gain new knowledge of how the gases near the photosphere move about and how they interact with one another.

Another special device used for studying the Sun is the *coronagraph,* invented by the French astronomer Bernard Lyot. This allows astrophysicists to observe the corona, the chromosphere, and solar prominences at any time without having to wait for the rare moments of a total eclipse of the Sun. Lyot had to overcome two obstacles that normally prevent us from seeing these things. The first is the extreme brightness of the photosphere, which, by contrast, makes everything near it too dim to see. Lyot overcame this problem by using a refracting telescope fitted with a metal disk that blocked out the image of the photosphere. In this way his instrument made its own artificial eclipse of the Sun.

The second problem—keeping out unwanted light scattered by the Earth's atmos-

phere—was more troublesome. To overcome this one he placed at the front of the telescope a long hollow tube to keep out light from the surrounding sky. And the inside of the tube was greased to trap floating dust particles that would otherwise scatter some of the light. In addition, all of the lenses in the telescope were polished as perfectly as possible so that they would be free of tiny light-scattering scratches. And finally, since even the best lenses are bound to scatter a little light, Lyot used only one lens for his object glass instead of the usual two.

By using the coronagraph from a high-altitude observatory, where the Earth's atmosphere is thinner than at sea level and so scatters less sunlight, astronomers can now observe or photograph different regions of the Sun's atmosphere at any time. And by using a spectroscope they can also obtain spectra of these regions.

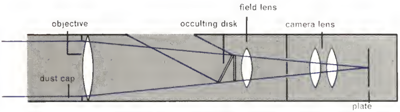
The results obtained by the coronagraph have been wonderful. For the first time in history, the corona has been observed in broad daylight. This has meant that instead of being able to observe the corona over an average of two minutes in the course of a year (during an eclipse), astronomers can now study it for weeks on end. What is more, coronagraph movies of solar prominences have been made and from them astrophysicists have discovered much about the chromosphere and sunspots.

When they obtain spectra of the Sun's surface, astrophysicists want to separate the lines of any spectrum very widely so that they can be examined in detail. The best way to do this is to use a grating spectrograph together with a telescope of very long focal length. (A telescope is said to have a long focal length when the image is brought to a focus a long way from the object glass or mirror.) One method is to fix the telescope vertically and to construct a tower to hold it. This has been done, for example, at Mount Wilson and Kitt Peak observatories in the United States and at Arcetri, Italy.

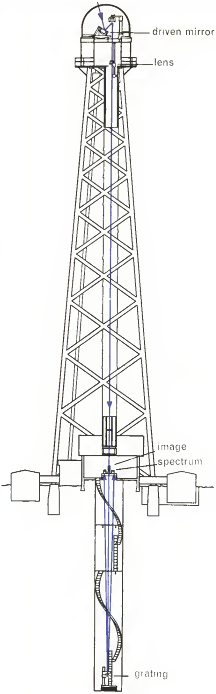
The other way is to lay the telescope along the ground and so construct a horizontal solar telescope, like those at Mount Wilson in California and at Cambridge in England. Whichever method is used, the telescope remains fixed and the sunlight is fed to it by two large flat mirrors, one of which is driven to follow the Sun. These two mirrors together form what is called a *coelostat*, which means "holding the heavens still," and that is just what they do.

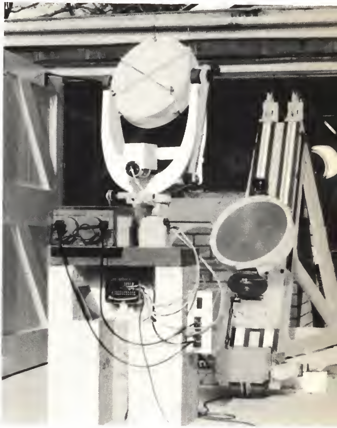
The light is passed from the coelostat to an object glass with a focal length of 100 feet or more, and an image of the Sun is thrown on to the slit of a spectroscope. In the Mount Wilson and Arcetri tower telescopes this slit is at ground level and the light from it passes to the lens and grating of a spectroscope at the bottom of a deep well, where they are kept cool.

The horizontal solar telescope is constructed in a similar way, but instead of the lens and grating being at the bottom of a well they are at the end of a long tunnel. The tunnel is usually made of wood and equipped with double walls so that, again, the spectroscope is kept cool. Images of the Sun a few feet across are obtained with these instruments. Spectra, showing thousands of lines, can be photographed from only one tiny part of a sunspot or the photosphere.



Except during a solar eclipse, the light from the photosphere is so intense that it prevents us from seeing the Sun's corona. The French astronomer Bernard Lyot overcame the problem with the coronagraph. It consists of a refractor fitted with a metal disk to eclipse the photosphere artificially. A long tube keeps out unwanted light.

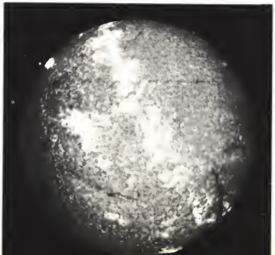




A coelostat is made up of two mirrors, one fixed (as the solar telescope itself is) and the other driven to follow the Sun. The coelostat above feeds the Sun's light into a telescope at Cambridge, England.

This photograph shows only the part of the Sun's light that is produced by calcium atoms. Such photographs are made with the spectroheliograph.

To spread solar spectral lines out widely we need a grating spectrograph and a telescope of very long focal length. The long telescope is sometimes housed in a high solar tower. Above is a diagram of the solar tower at Mount Wilson, California. At its top is the coelostat. Near the bottom is the spectrograph.



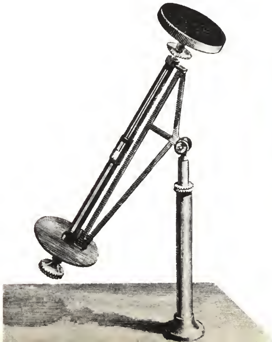
Measuring Heat and Light

Astrophysicists are not only interested in the light from the Sun, but also in that part of its radiation that reaches us in the form of heat. They want to measure the heating effect both of infra-red radiation and also of visible radiation. For this purpose they use an instrument known as a *pyrheliometer*. It consists of a blackened metal disk whose capacity to store heat is known. When a known amount of sunlight is allowed to fall on the disk, the temperature of the disk rises. By measuring the degree of rise the astrophysicist can then work out how much heat energy is being given out by the Sun.

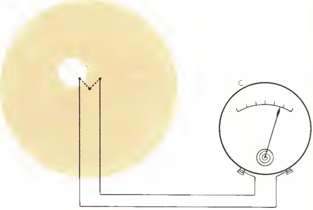
We saw in the last chapter that the Earth's atmosphere lets through some wave lengths more easily than others. With an instrument called the *bolometer* we can learn exactly how the atmosphere does this. The bolometer can be used also for measuring the temperature of the planets and even the temperatures of a few very bright stars. The instrument works on the principle that when a piece of metal is heated, less electricity flows through it than when the metal is cold.

The bolometer consists of two very thin strips of platinum. The first strip is placed at the focus of the telescope where it can absorb radiation, while the second strip is placed where it is shielded from the radiation. The two strips are linked in a special electric balancing circuit. The circuit comes out of balance when one strip becomes hotter than the other; and the amount of correction needed to restore the balance enables us to measure the temperature of the star or planet being observed. By using a bolometer and a spectroscope together astrophysicists can also find how much energy at various wave lengths passes through the Earth's atmosphere.

Another device used to measure the temperature of the planets and bright stars is the *thermocouple*. It, too, uses an electric circuit to detect temperature. With the bolometer and thermocouple astronomers have been able to revise their measures of the true brightness of stars by taking into account the radiation absorbed by the atmosphere. They can also measure temperatures found on the planets and the Moon. The surface of the



Under the black disk of this pyrheliometer is a thermometer. One reading is taken when the disk does not face the Sun and one when it does. The rise shows what heat energy the Sun emits.



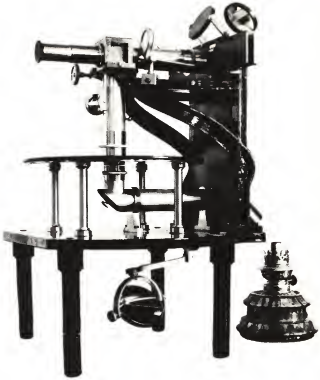
A thermocouple is based on the fact that when energy falls on a junction of two different kinds of wire a current flows. If one junction receives some energy from a planet while the other is kept cool, the current is sufficient to be registered by a galvanometer.

Moon, for example, ranges from 100° C. at noon on its equator to something like –157° C. at lunar midnight. While the summer temperature of Mars reaches 22° C.—quite pleasantly warm—nights on the planet are gripped by a temperature of –83° C., cold even for the Antarctic.

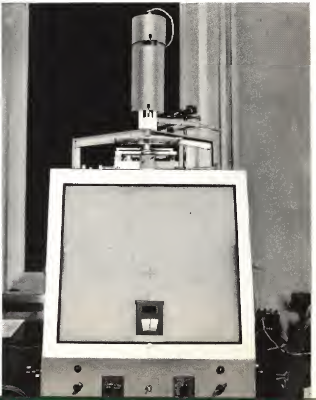
In addition to the intensity of heat of the planets and stars, astrophysicists also want to know how much light we receive from these bodies. To measure light intensity a *photometer* is used. One kind, still in wide use, although it is an old invention, has an electric bulb that produces a starlike image whose brightness and dimness can be regulated. When the observer adjusts the image so that it is of the same brightness as the star he is studying, he is able to measure a star's apparent brightness. But most measurements of light intensity are now made either electrically or by photography.

The brighter a star, the larger and denser the image it makes on a photographic negative. So if we photograph a number of stars we can tell how bright each one is by comparing it with the others on the plate. This kind of measurement is often carried out with a *microphotometer*. In one type of microphotometer a light is passed straight through the plate on to a photoelectric cell, which gives out a minute electric current when light falls on it. The strength of the current depends on the amount of light received, so by measuring the current produced by the light from each star image we can tell just how bright each image is.

A new kind of photometer measures the sizes of the star images appearing on the photographic negative as dark spots against a clear background. With this apparatus it is possible to distinguish between two stars that differ in brightness by less than one per cent. If a red color filter is used in a photometer a red star will appear brighter than when seen through a blue filter. For a blue star exactly the opposite is true. By comparing these different values of brightness obtained by filters astrophysicists can provide definite measures of a star's color. This *color index* is important in studying life cycles of stars.



An old microphotometer (above) compared the density of a star image on a photograph with an artificial light. A modern one finds the brightness of a star from the image with the aid of a photoelectric cell and electronic circuits.



Radio Waves from Space

All the instruments we have described so far are used to study radiation that we receive from stars and galaxies in the form of light or heat. What of the longer wave length radiations we know as radio waves? To receive them we have to use radio telescopes.

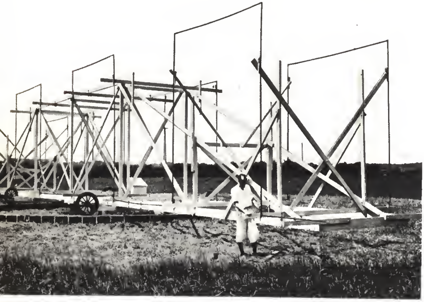
These instruments are a new development. It was not until 1932 that Karl Jansky, an American radio engineer, found that some radio waves seemed to be coming from outer space. Another American, Grote Reber, an amateur radio ham, confirmed this in 1938. Investigations came to a stop during the Second World War but in 1946 the work was again taken up and the radio telescope was designed.

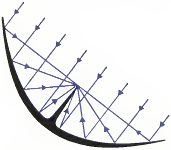
A radio telescope consists of two main parts—an aerial and a radio receiver. The aerial, or "dish," is the more spectacular part and the one that people usually think of when a radio telescope is mentioned. However impressive, the aerial is only one part of the equipment. The other is the radio receiver that the aerial feeds.

The receiver of a radio telescope must be a very sensitive instrument. Even with a large aerial the radio signals picked up from space are extremely weak compared with radio waves that operate our home receivers. Another difficulty is that unwanted radio signals —called "noise"—are picked up, too. This means that the receiver has not only to be very sensitive, but it also must be able to sort out the wanted signals from the noise. Radio engineers have developed a number of ways of getting receivers to do this. One ingenious device selects the wanted signals from space and then amplifies them into very strong signals. These signals, like the ones from other types of radio telescopes, are then fed into a recorder that works a pen and so enables a graph of the signals to be plotted automatically.

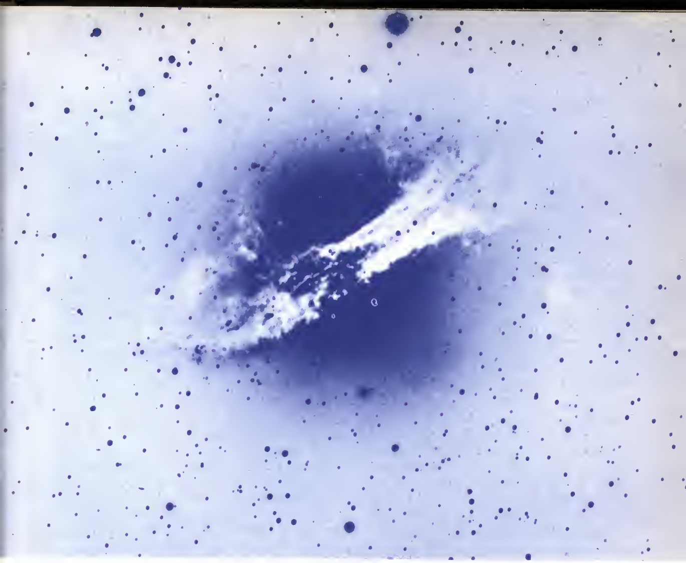
The aerials of radio telescopes, although they vary widely in design, all have one thing in common. Each acts in a way similar to the mirror of an ordinary reflecting telescope. The reason radio-telescope aerials look rather different from a reflecting-telescope mirror is that the wave lengths they collect are much longer than those of light. The wave lengths the radio astronomer deals with are only a small part of the total range emitted, as mentioned on page 49.

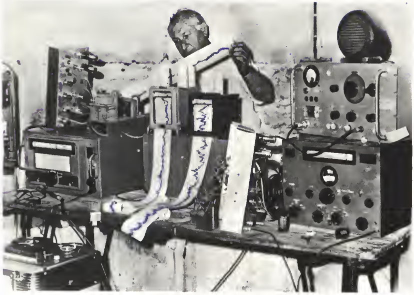
If the astronomer wishes to receive very short solar wave lengths and radio radiation from stars, galaxies, and gas in space, he must use a bowl reflector. For very short radio waves the bowl is covered inside with thin





In the 1930s an American radio technician, Karl Jansky, realized that some radio waves reach us from outer space. Here Jansky is seen with the first equipment specially designed to receive such signals. The diagram shows how the bowl of a modern radio telescope reflects waves reaching all parts of its surface to a receiving aerial.





Many sources of radio waves lie beyond the observation of even the largest optical telescopes, but some can be identified and photographed. This picture shows a very powerful radio source, catalogued as NGC 5128. Some astronomers think that we are here looking at two distant galaxies in collision.

Here is part of the equipment used by Mr. F. W. Hyde, a British amateur radio astronomer, at his private observatory in Essex. Near the center of the picture is a strip of paper on which a pen recorder has automatically plotted a graph of signals received.

copper sheets, but for waves of a meter or more in length a reflecting surface of wire netting is perfectly satisfactory, since such waves are too long to "slip through" the holes in the netting.

We saw earlier that a large optical telescope can resolve finer detail than a small one. This also applies to radio telescopes. Since the aerial reflector, or mirror, of a radio telescope is made of metal instead of glass, it can be built as big as we choose without running much risk of losing accuracy. The only limitation is that it must not be too heavy to be steered. Huge steerable radio telescopes of this kind are in use at Jodrell Bank in England, Sydney in Australia, and also in California and West Virginia in the United States.

Still greater power to resolve detail can be obtained by using more than one radio telescope at a time and combining the waves received by one aerial with those received by another. By combining the 250-foot telescope at Jodrell Bank with a smaller aerial $12\frac{1}{2}$ miles away, radio astronomers have achieved a resolving power 45 times greater than they could get with the large telescope alone. A radio telescope that uses two or more aerials at once is called an *interferometer,* because the greater resolving power is obtained by allowing the radio waves received by one aerial to "interfere" with those from the other.

Some of the special interferometers designed in recent years are surprisingly large. In Cambridge and Sydney instruments with fixed aerials some hundreds of yards long are in use. Although the aerials are fixed, in the sense that they cannot be steered like the great bowl reflectors, they can move a little in a north-south direction. Movement in an east-west direction is left to the Earth as it spins daily on its axis! In Sydney the aerials are arranged in the form of a cross and the instruments (there are two of them) are known as the Mills Cross, after their inventor Bernard Mills. In Cambridge one aerial 500 yards long is used in conjunction with another 190 feet long. The smaller aerial, about a quarter of a mile away from the larger one, is mounted on a kind of railway track so that it can move, as well as tilt, in a north-south direction. When two aerials are used as if they made up a single gigantic radio telescope, they not only increase resolving power but also become much more sensitive to very faint radio signals. In California two 80-foot steerable bowl reflectors, each mounted on rails, are used in this way. Radio interferometers are now widely used in

The 10-foot bowl of this radio telescope at Goth Hill, Canada, is comparatively small. The only limitation to the size of such bowls is that they must not be too heavy to be steered.

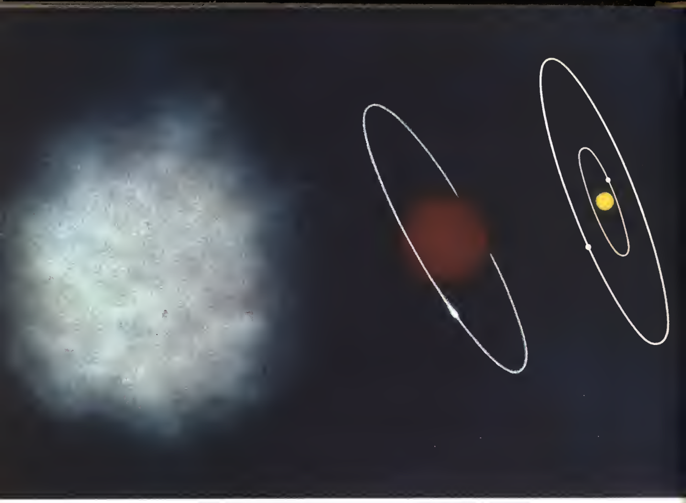
This huge Mills Cross telescope in Australia uses two aerials. Some north-south movement is possible, but east-west motion depends on the Earth's rotation.

radio astronomy and are providing astrophysicists with new information about distant galaxies, especially the numbers there are in the far distant parts of space.

Radio telescopes are also giving us new information about the Sun and the planets. The Sun's corona, for example, has been traced out to a distance of more than 20 million miles by radio telescopes, and many details about flares and sunspots have been found. Some radio signals also come from Jupiter, but the reason for this is not yet fully understood.

Within our own Galaxy several nebulae send out radio signals, especially stars that have become novae. In fact, one of the strongest sources of radio signals is the Crab Nebula, which is the remains of a nova explosion recorded by Chinese astronomers in the year 1054. To date a list of more than 2000 radio sources has been compiled. With radio telescopes astronomers can "hear" stars that are far too distant to be seen with optical telescopes. Radio telescopes are also the main instruments with which astronomers will one day try to communicate with intelligent beings that may exist on other planets, —planets orbiting around stars far distant from the Sun. But we must leave this exciting possibility to the last chapter.

With the giant radio telescope at Cambridge, England, nebulae 5000 million light-years away have been observed. Shown below is the fixed east-west aerial, nearly 500 yards long. Teamed up with it is the smaller one above, which can be hauled north and south over a railroad track.



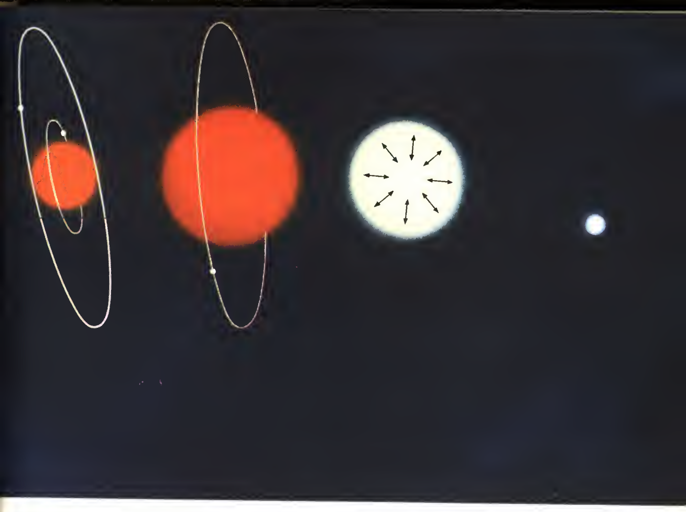
4 The Life and Death of Stars

At one time astronomers regarded the stars as being eternal, without beginning or end. Today we know that the stars do not go on shining forever, that they have a life history and eventually come to an end and "die."

A star like the Sun, for example, begins within the Galaxy as a cloud of dust and gas that collects and forms a sphere. As the matter making up this new body gradually packs itself more and more tightly around the center, the temperatures within increase, and they continue to rise until nuclear reactions are set up. In this way the star continues to shine for thousands of millions of years. After an immense time, when the star exhausts its "fuel" of hydrogen gas, the nuclear reactions cease and the star stops shining. What probably happens next is that the star shrinks into a comparatively small but extremely dense dark body that is invisible in the sky.

Brightness and Temperature of Stars

To study the lives of the stars in detail we must begin by examining what we can about the stars that we see shining now, and learn how they differ from one another. To begin with, they differ in brightness. Astronomers measure the brightness of stars in units called *magnitudes*. In some respects this term is



misleading, for it has nothing to do with the size of stars. What is more the magnitude scale is really a scale of dimness rather than of brightness. A star with a magnitude of 1 is brighter than one of magnitude 2; a star of magnitude 2 is brighter than one of magnitude 3, and so on. The first man to make an accurate catalogue of stars and to remark on their brightness was the Greek astronomer Hipparchus, who lived around 150 B.C. About 300 years later Ptolemy extended Hipparchus's work and compiled a catalogue that used the term magnitude. Ptolemy, and probably Hipparchus as well, recognized six magnitudes of stars that can be seen with the

Most astronomers believe that a star like the Sun passes through the stages shown above. It begins as a rotating cloud of gas and dust that condenses slowly into a huge globe and perhaps forms the beginnings of a planetary system. As this globe condenses further, nuclear reactions begin and it is now a true star (third picture). In millions of years it grows brighter, then expands (picture four) until it becomes a red giant (five). Later it becomes a pulsating star (six) and finally a "dead" white dwarf.

naked eye, and this system of magnitudes is the one that we use today, but with greater precision.

In this system, a star of magnitude 1 is exactly 100 times brighter than a star of magnitude 6. Since there are five steps of magnitude between 1 and 6, this means that a star of one magnitude is just over $2\frac{1}{2}$ times brighter than a star of the next magnitude. This is simply because $2\frac{1}{2} \times 2\frac{1}{2} \times 2\frac{1}{2} \times 2\frac{1}{2} \times 2\frac{1}{2}$ makes nearly 100. Since the magnitude scale moves upward or downward in even steps, we can extend it as far as we need in either direction. For instance, we can include stars that are far too dim for the naked eye to see, as we do when we speak of the 200-inch telescope photographing stars of magnitude 21. We can also extend the scale to include very bright stars. To do this we have to recognize that a star $2\frac{1}{2}$ times brighter than magnitude 1 must be magnitude 0, and one $2\frac{1}{2}$ times brighter than magnitude 0 must be magnitude -1. On this scale the full Moon has a magnitude of $-12\frac{1}{2}$, and the Sun has a magnitude of about $-26\frac{1}{2}$.

When we use the magnitude scale in this way, we are simply stating the brightness of stars as they appear to us on Earth; we are giving their *apparent magnitude*. But two stars that look equally bright may actually be very different in brightness, because one is much nearer to us than the other. To compare the true brightness of two stars—to give their *absolute magnitude*—we must know not only how bright they appear, but also how far away they are. When we know how bright each one appears and also how far away each one is, we can work out how bright both of them would be if they were at the same distance away from us. This gives us their absolute magnitude, or true brightness. When astronomers work out absolute magnitudes they use a fixed standard of distance that tells us how bright stars would appear if they were all exactly $32\frac{1}{2}$ light-years away from us.

The second important fact we know about the stars is that they differ in temperature. At the end of the second chapter we found that we could classify them in hottest-to-coolest order by their spectra (O, B, A, F, G, K, M). At one end of this range are the hottest O-type stars in which many atoms have been ionized, or stripped of electrons, and which give out most of their radiation in the blue part of the spectrum. At the other end are the M stars, radiating most strongly at the red end of the spectrum. Because molecules are present in the atmospheres of the coolest M stars, their temperatures cannot be much more than about 2000° C.—the temperature

of a hot gas flame. Molecules are not found in O, B, A, F, G, and K stars because the very great heat breaks them down into their separate atoms.

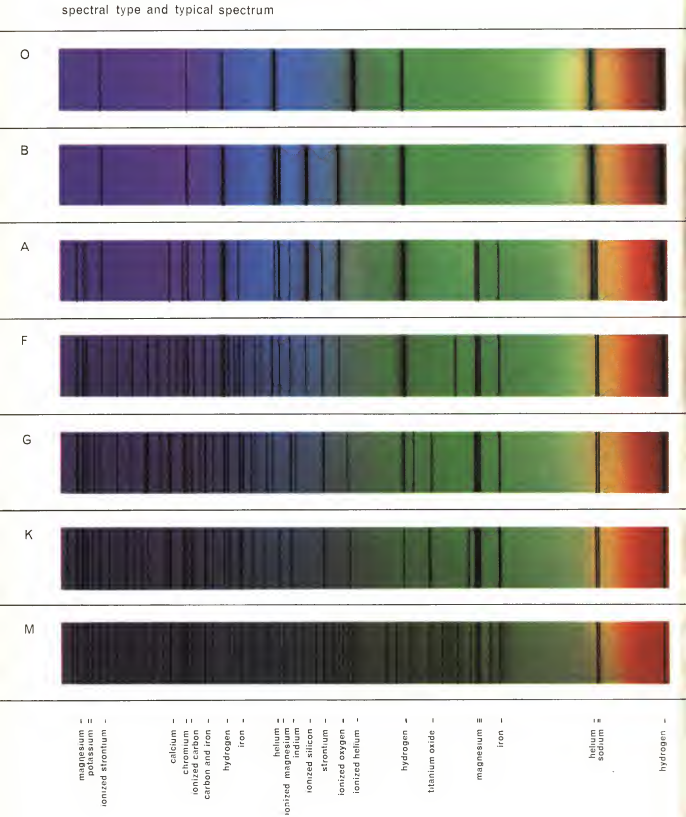
Measurements of absolute magnitude of stars of various spectral classes make it clear that the hotter the star, the brighter it is—at least this is true in most cases. This relationship between absolute magnitude and temperature is very important to astrophysicists when they attempt to work out the life cycle of stars. Since the majority of stars obey this main-sequence relationship between spectrum and brightness they are usually referred to as *main-sequence* stars. They range from the hottest O stars to the coolest M stars. On pages 86 and 87 is a table showing many important facts about each of the seven main spectral classes. These facts, and the deductions that can be made from them, enable the astronomer to understand a great deal about the way stars behave.

Of course the stars do not all fit into quite such a simple and tidy pattern as our table might at first suggest. There is a gradual change from one spectral type to the next. O-type stars merge into B, B into A, and so on. To help in placing the stars as nearly as possible into their correct positions in such a table, astrophysicists subdivide each spectral class into 10 steps. An A5 star, for instance, is just midway between the coolest B stars and the hottest F stars. Similarly a star only a little cooler than the coolest A stars (A9) will be labeled F0; a star a little hotter than the hottest G stars will be labeled F9. The position of a star within each main class is decided purely by the strengths of the various lines in its spectrum.

Because of certain special features in their spectra four other types of stars are included in the classification systems, and all four fall outside the main sequence O to M. One of these special groups of stars is the rare type W stars, which are much hotter than even O-class stars and which show broad *bright* bands of hydrogen and helium. Their temperatures can reach 100,000° C. At the other end of the scale are stars of type N, whose spectra show bands produced by the molecules of carbon compounds. The surface temperatures of N stars probably range between 3000° and 2000° C. Slightly hotter than these are stars of type R, which form a kind of link between N stars and G stars. In other words we can say that some stars "branch off" from the main sequence at G. Instead of following on to be classified as K or M, they have to be considered as being different, and we therefore classify them as R or N. There

All the street lamps shown in the top picture opposite have the same absolute magnitude. In other words they all have the same true brightness. Yet in the photograph below their apparent magnitudes (*seeming* brightnesses) vary. A, B, C, and D, all equidistant from the camera, appear equally bright. (E, F, G are dimmer because they are at an angle and we see only part of their light.) Remaining lamps look dimmer just because they are farther from the camera. So it is with stars. In a photograph of the Southern Cross a few stars stand out as extremely bright. Certain others that look dim are really just as bright but are much farther from us.

Spectra, Temperatures, and Brightnesses of Typical Stars



atoms producing main lines of spectrum	color of main radiation	temperatures at surfaces of stars	brightness (absolute magnitude) of specimen stars	
ionized helium, neutral hydrogen and helium		35,000°–40,000°C	λ Cephei	−6·5
neutral helium; ionized silicon, magnesium, oxygen and nitrogen; neutral hydrogen		11,000°–35,000 C	η Orionis Alkaid	−5 −1·5
metals (especially calcium) giving weak lines; hydrogen giving very strong lines		7500°–11,000°C	Sirius Vega	−1·3 −0·5
metals (especially calcium) giving strong lines, hydrogen giving fairly weak lines		6000°–7500°C	Procyon	3
potassium giving a strong line; neutral metals (fairly strong lines) ; hydrogen (weak lines)		5100 –6000°C	Sun Capella	−5 −0·5
neutral metals giving strong lines; hydrogen (very weak lines)		3600°–5100°C	Arcturus 61 Cygni	0 8
molecules of titanium oxide (strong bands)		2000°–3600°C	Betelgeuse Antares many others	−5·6 −5·1 12 or 13

Scientists believe that stars behave in much the same way as a *black-body* radiator, like this iron poker. When cold the poker is dull because it absorbs all incoming radiation.

When heated to comparatively low temperatures the poker will give out a dull red glow—the predominant color emitted by the coolest stars of the main sequence, those of type M.

When hotter the poker glows brighter and its tip is orange, the color of a K-type star. Heat it more and it becomes whitish, like an F-type star, and eventually bluish-white.

is another branching off from the main sequence after type K. Some stars that are cooler than the K type cannot be classed as M stars because their brightness is not constant and their spectra show bands produced by the molecules of zirconium oxide and titanium oxide. These are labeled S stars.

By looking carefully down the columns of our table we can gather two very important facts. First, as we move downward from O to M we notice that the main color of the stars changes from blue to red. Since we know that a very hot flame gives a blue light while a cooler one gives a red light, this is clear evidence that the O stars are the hottest and the M stars the coolest. Next we see that there is more ionization in O stars than in those lower down the table. Since high temperatures produce more ionization than low temperatures, this evidence supports the evidence of color. And it is from these two kinds of evidence that astrophysicists have been able to work out the surface temperatures of the various classes of stars.

All this evidence about temperature and color also provides a clue to the way stars radiate energy. It leads astrophysicists to believe that, generally speaking, the stars behave like *black-body* radiators. A black-body radiator is an ideal body that will radiate brightly when heated and absorb all wave lengths of energy when cold. This means that, like a poker, when it is cold it will appear completely black, but as its temperature is increased it will first glow a dull red, then a brighter red, and as it becomes hotter still, it will emit yellow light, white light and, finally, light of a bluish-white color. This, of course, is just what we find when we move along the main sequence of stars from M to O.

Fortunately scientists have discovered exactly how black bodies behave when they are heated. Provided we know the size of a black body we can tell quite accurately how bright it will be at any particular temperature. Similarly, if we know its temperature and its brightness we can work out its size. So if the stars really do behave like black bodies we can work out their size from our knowledge of their temperatures and their true brightnesses.

Before continuing with this idea of the size of stars, we should return to our table again. We see there that the Sun, a typical G-type star, has an absolute magnitude of 5. Yet Capella, another typical G-type star, has an absolute magnitude of $-\frac{1}{2}$, which means that it is more than 150 times brighter than the Sun. A similar situation arises with the K-

type stars. Arcturus has an absolute magnitude of 0, and 61 Cygni has an absolute magnitude of 8, a difference in brightness of more than 1500 times. In M-type stars the difference in brightness is even more surprising. Betelgeuse has an absolute magnitude of −5.6 and Antares of −5.1, but many M stars, with magnitudes of 12 or 13, are far too dim to be seen with the unaided eye and are more than a million times dimmer than the bright stars of the same class. All this means that we must not assume that all stars of the same spectral class have the same true brightness, because quite obviously this is not so in the case of stars of types G, K, and M. The simple relationship between temperature (which is indicated by spectral class) and brightness holds good only for certain stars on the main sequence.

In fact astrophysicists are forced to recognize that there are two classes of brightness among stars belonging to the same spectral type. The bright stars of a given spectral type are giant emitters of radiation while the dim ones, by comparison, are dwarf emitters. The words *giant* and *dwarf* are used as descriptions of these two kinds of star, and strictly speaking they refer simply to the absolute brightness of stars. But do they also give some indication of a star's size?

The Size of Stars

We cannot answer this question by looking through a telescope and measuring the sizes of different stars, because even in the largest telescopes all stars appear as mere dots of light. What we can do, however, is to make use of our theory that the stars behave like black-body radiators. We have seen that once we know the true brightness and the temperature of a black body we can work out its size. Because we know the temperature and true brightness of many stars we can calculate their diameters. Let us see what some of these calculations reveal.

Among the G-type stars we find that Capella, 150 times more brilliant than the Sun, has a diameter 12 times larger, measuring more than 10 million miles across. With K stars the range of diameters is even greater. The dwarf star 61 Cygni is about three quarters the size of the Sun and so is less bright, but the bright giant Arcturus is 30 times larger, with a diameter of 25 million miles. But it is in stars of type M that the giant and dwarf range reaches its most surprising proportions. Dwarf M stars are very small, having diameters less than a third of that of the Sun, although some M giants are fantastic in size, Antares being 300 times larger than the Sun and Betelgeuse almost 400 times larger. This makes the diameter of Antares 252 million miles and that of Betelgeuse 336 million miles. If Antares were placed where the Sun now is, it would envelop the orbits of Mercury, Venus, and the Earth. Placed in the same position, Betelgeuse would envelop Mars as well. So bright,

Here the diameters of four stars are compared. The Sun, on the same scale, would be the size of the central compass hole.

and incidentally so big, are these two stars compared with the dwarf members of their spectral class, that they are called *supergiants*.

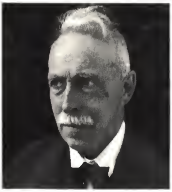
The largest supergiant discovered so far is the star ε (epsilon) Aurigae which is of type K5. This star has a diameter 2000 times larger than that of the Sun. If placed in the center of the Solar System it would extend nearly to the orbit of Saturn!

These calculations of star diameters depend on the theory that the stars radiate in the same way as black bodies. Is there any way that we can confirm that the measurements are correct? For giant stars that are not too far away from us there are two ways of checking. One is to make an accurate timing of how long it takes the limb of the Moon to blot out the light of the star. Because the Moon has practically no atmosphere, when it passes in front of most stars its clearly defined edge cuts off their light instantly. For supergiants, however, this cut-off happens gradually. With the help of a photometer it is possible to measure the instant when the cut-off begins and the instant when it is complete. We know how far away the star is, we know the speed at which the Moon appears to move across the sky, and our measurement now tells us how long the Moon takes to travel across the whole apparent diameter of the star. From all this we can work out the star's diameter. This method is still only experimental.

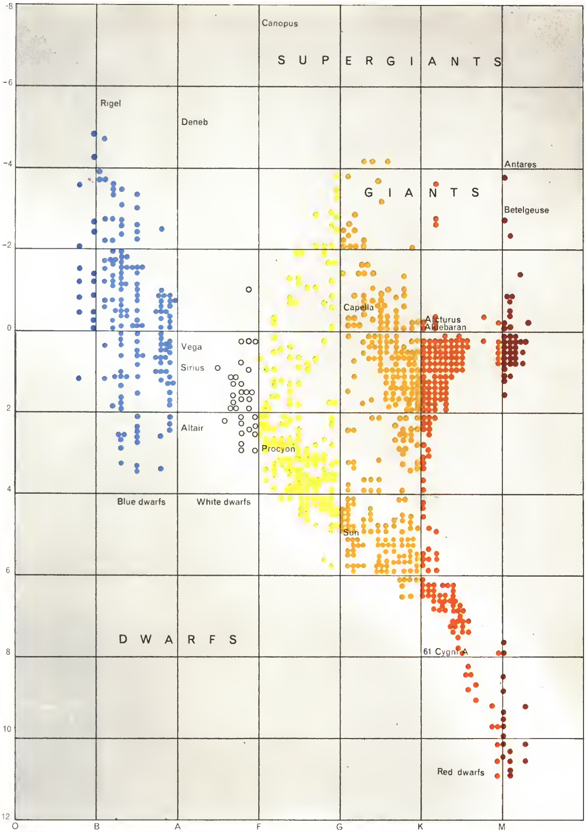
The second method of checking the diameter of a supergiant depends on splitting the light from the star into two separate beams and then mixing the beams together again. (A telescope fitted up so as to make the beams interfere with each other in this way is called an interferometer.) This second method, like the Moon method, gives results that confirm the calculations made from the black-body theory. This is a strong indication that the black-body theory is a sound one. So although we have no way of checking the size of dwarf stars, we can feel reasonably safe in accepting the figures that the black-body theory gives us for these small stars.

Discovering the sizes of stars is only one of the exciting possibilities opened up by the spectral classification in our table on pages 86 and 87. The spectral classification provides us with a starting point for many other investigations into the behavior of stars. To demonstrate this, we can draw up a special plan known as a *Hertzsprung-Russell diagram*—or *H-R diagram* for short—named after the two men who first arranged the facts in this way.

The H-R diagram shows at once that the hotter a star is, generally speaking, the greater is its absolute brightness. We can see, for instance, that many G, K, and M stars, which are cool, are also dim stars, or dwarfs, and that they fit very well into the general sequence of stars as they change in brightness and temperature from the bluish O stars at the top to the red dwarfs near the bottom. But what of the giants and supergiants? They do not lie along the general sequence



Hertzsprung (left) and Russell (right) invented a special way of showing the relationship between the temperature and the brightness of stars. In the Hertzsprung-Russell diagram opposite, the nearer a star is to the top the lower is its absolute magnitude and thus the greater is its true brightness. The nearer a star is to the left-hand edge the higher is its temperature.



Since this diagram was made different absolute magnitudes have been assigned to some stars.

of stars. We should expect to find them all among the hot O and B stars, ranging in temperature from 11,000° C. to 40,000° C., but in fact there are cool M and K supergiants, like Betelgeuse and Arcturus with temperatures ranging from 2000° C. to 5100° C. These stars appear near the top right-hand part of the diagram along with giants like Aldebaran and Antares. All of these stars must be plotted above and away from the general run of stars. This is true also of certain other very bright stars like Canopus, an F-type supergiant 100,000 times brighter than the Sun, and Rigel, an A-type supergiant 10,000 times brighter than the Sun. These stars lie across the top of the diagram.

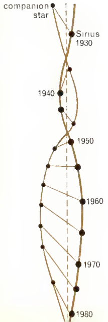
The big question facing us now is to explain why the giant and supergiant stars (in addition to others as well) must be given special positions in the H-R diagram. Before we find out why this is so, what can we say about the life history of a typical star, based on the facts we have looked at so far? From these facts we can only make a guess, using the theory that stars use up their energy and "fuel" as they shine and so shrink smaller and smaller. This guess would lead us to expect that stars begin as red giants or supergiants; then, as they contract and become hotter, we might expect them to enter the main sequence as O-type stars and, using their energy, gradually cool and shrink through the yellow and orange stages along the main sequence until they become red dwarfs. This is, in fact, exactly the guess that was made by Henry Norris Russell, one of the two men who invented the Hertzsprung-Russell diagram in the early 1900s. But it was only a guess. Before astronomers and astrophysicists could tell whether it was true or false, they had to learn much more about the stars, especially about their masses.

Binaries and the Masses of Stars

It happens that the main clue we have to the massiveness, or weight, of stars, comes from a study of what are called *binary* systems. A binary system consists of two stars comparatively close together so that they orbit around each other. Although these "double stars" cannot be seen as two separate stars by the naked eye, a telescope splits them and surveys reveal that there are a vast number of these systems. For instance, we can see the Dog Star, Sirius, but without a telescope we could never see that it has a small companion, the "Pup," and that the two together form a binary. Mizar, one of the stars in the handle of the Dipper, also turns out to be a double star when we view it through a telescope.

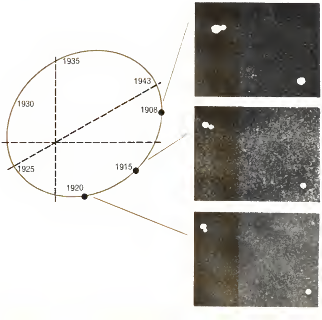
If we observe a binary system over a number of years, we can work out the shape of the orbit that the two stars follow and how long they take to move around it. Once that is done we can calculate how the mass of one star compares with the mass of its companion star.

At that stage in our investigation we can say, for example, that one star is five times



The three photographs on the right show how the two stars of the binary Kruger 60 looked in three different years. From a number of such observations the orbit was worked out.

If Sirius were a single star it would make a straight track as shown by the dotted line at the left. In fact it makes the snaking track of the thick curve. This led astronomers in 1844 to suspect the presence of a companion. The companion was first observed in 1862.



as massive as the other, or ten times as massive, or whatever the case may be. But we cannot yet say how massive either of them is compared with the Sun or with the Earth. In other words, we know their comparative but not their individual masses and the reason for this is not hard to understand. So far we have discovered only the shape of the orbit and how long it takes the two stars to move around it. We do not yet know the *size* of the orbit, and this means that we do not know how far apart the two stars really are or the speeds at which they must be moving in their orbit. But we can find the size of the orbit if we can measure how far away from us the whole binary system is.

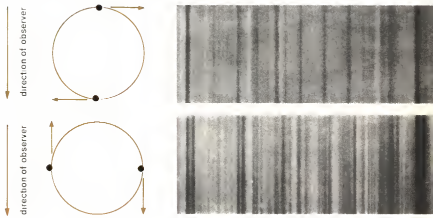
Fortunately there are many binary systems near enough to us for their distance to be measured, so the actual mass or weight of a considerable number of these stars has been found.

Plotting the orbit of a binary is by no means easy. First, the stars concerned are all so far away that their orbits appear extremely small. We can detect them only by delicate measures allowing us to compare the position of one of the stars with the position of the other, from time to time. Next, many binaries take several years or even several decades to complete one orbit. This means that a great many observations have to be made and careful records kept before we can get all the information we need.

The observations are made either at the eyepiece of the telescope, or else with the help of photography. For visual observations a special micrometer is fitted to the eyepiece, which enables the observer to make extremely accurate measurements of the angle and the apparent distance between the two stars. When photography is used, exposures are made from time to time and the positions of the two stars on each plate are measured.

Some binary systems have been detected even though their stars are so close together—or so distant from us—that they appear only as a single star in the telescope. One way of detecting them is by observing the tiny dot of light (called a diffraction disk) they produce in the telescope. If the disk appears elongated, it is likely that the elongation is being produced by two stars very close together, and not by a single star. We can then use an interferometer to separate the two overlapping dots and to measure the angle between them. But this method will not work if the two stars are too close together or too far away from us. Binaries can then be recognized and their orbits measured only with the aid of a spectroscope; such stars are known as *spectroscopic binaries*.

Because the two stars in a binary system are moving around each other, there will be times when one will be moving toward us while the other is moving away; but there will also be times when both stars are moving only across our line of vision. When both of them are moving across our line of vision they will produce a spectrum with clear, single lines. But when one is moving toward



The spectroscope allows us to detect many binaries that are too far away for the telescope to resolve. Here we see how. There are times (top row) when neither star of the pair is moving toward us or away from us. Both move only across our line of sight, producing quite ordinary spectrum lines. Later (bottom row) one is moving toward us and the other away from us. Spectrum lines from one are shifted toward blue while spectrum lines from the other are shifted toward red.

us and the other away from us, the lines produced by one star will show a shift toward the blue end of the spectrum, while those produced by the other will show a shift to the red end of the spectrum. When that happens the lines produced by the binary system as a whole will be doubled.

The time taken for this change in the spectrum lines—from single to double and back to single again—enables the astrophysicist to discover how long the stars take to complete half their orbit around each other. From this he can then find the complete orbiting time.

Sometimes the astrophysicist does not even observe a double spectrum. This happens, for example, when one star is much dimmer than the other. Yet even then the brighter star will show a regular change from red shift to blue shift to red shift again. This enables the astrophysicist to plot the changes in the star's velocity—to make what is called a *velocity curve*. Since both stars of a binary system take exactly the same time to complete their orbit, the information he gets from this velocity curve will apply to the dim star as well as to the bright one. The velocity curve can also tell the astrophysicist whether the orbit of a binary system is almost circular or very oval. If it is almost circular the change from red shift to blue shift and back again will be a steady, gradual change. If, on the other hand, the orbit of the binary has the form of a long, narrow oval the change will take place at a very uneven rate.

In some binaries each star in turn passes in front of the other, hiding some of its light. Here are two examples of light variations from binary systems. In both, the deeper dips occur when the dimmer star eclipses the brighter one. Shallow dips occur when the brighter one eclipses the dimmer one.

When one star is exceptionally bright and the other very dim we see only the bright one's spectrum. By timing how long the lines take to shift first to blue then to red we can work out the orbital velocity of the system. The top velocity curve here indicates a roughly circular orbit, and the second a more elliptical orbit.

William Herschel (on the left) and Friedrich Wilhelm Struve began the study of binaries.

Even though the astrophysicist cannot see a spectroscopic binary, the velocity curve he makes tells him not only how long the two stars take to move around their orbit, but also what the shape of the orbit is like. It is at this stage that he can also discover something about the combined mass of the two stars take to move around their orbit, but cannot discover the individual mass of each.

The astrophysicist cannot work out any sound theory about the life cycles of the stars until he has collected as much information as possible about their masses. Since binaries are the main source of this kind of information he cannot afford to neglect any of them. Another special class of binaries he studies are called *eclipsing binaries.* These are double stars whose orbit lies in such a position that we can see it only "edge-on." Very often one of the two stars in such a system is bright and the other one dim. Sometimes we receive light from both stars; at other times the dim one eclipses the bright one; at still other times the bright one eclipses the dim one. From the changes in the amount of light we receive from the system as a whole, astrophysicists can work out the shape of the orbit and the relative masses of the two stars.

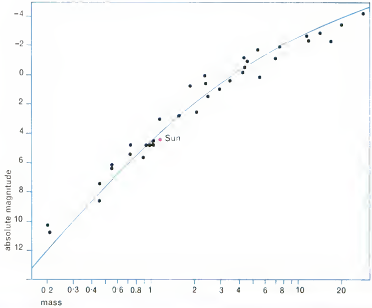
It is more than a hundred years now since astronomers first began to make a special study of binaries, and during that time the masses of a great many of these stars have been calculated. Let us see now how that hard-won information is being used.

We can begin by making a diagram somewhat like the Hertzsprung-Russell diagram on page 91. But this time, instead of showing the spectral classes O, B, A, and so on, along the bottom of the diagram, we show mass. Each point on our diagram will now tell us additional facts about the stars. The farther to the right of the diagram a star is, the greater its mass. And the nearer the top of the diagram it appears, the greater its *luminosity,* or true brightness. We can now see at once that the least massive stars—those that contain least material—are the dimmest ones. The most massive stars—those that contain most material—are very bright. And the change from one to the other is quite smooth and gradual. We already know that O- and B-type stars are, in general, bright while K- and M-type stars are, in general, dim. So we can safely say that the O and B stars will generally be more massive than the K and M stars.

As we might expect, there are some exceptions to this rule. Stars such as the "Pup" (the companion of Sirius) are known as *white dwarfs,* and they do not fit into the general scheme. They are very dense stars but nevertheless very dim. There are also certain stars of low mass that are very bright. But what matters most is the fact that the bright O- and B-type stars are, in general, more massive than the dim K and M stars.

This relationship between the mass and luminosity (or absolute brightness) is very important in helping us to understand the life

It is from studying binaries that astronomers have gained most of their knowledge about star masses—the amounts of material in various stars. This graph plots the masses of a number of stars (horizontal scale) against their absolute brightness (vertical scale). The curve of the graph shows that in general the most massive stars are also the brightest.



and death of stars, but it is equally important to know what kind of material lies below a star's surface. In all stars along the main sequence, hydrogen is by far the most abundant element, with helium as the runner-up. In fact hydrogen and helium together make up most of the entire mass of a star, all the other elements being present in very much smaller quantities. As an example we may take the Sun, which is quite like other main-sequence stars in this respect. Just over 90 per cent of its material is hydrogen and just over 9 per cent is helium. The remaining fraction of one per cent is made up of other elements, among which carbon and nitrogen are the main ones.

How Stars Age

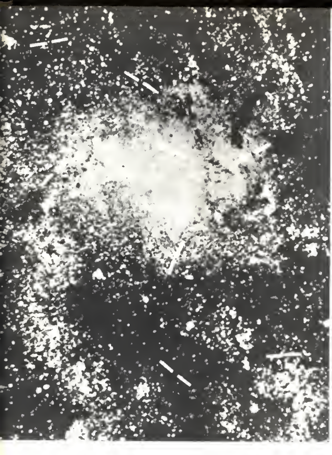
As a star ages it constantly uses up its hydrogen "fuel." As its hydrogen supply gradually decreases the amount of helium gradually increases. In the second chapter we found that there are two main kinds of atomic reaction responsible for this. The first kind builds up helium from protons (which are simply hydrogen nuclei). The second turns hydrogen and carbon nuclei into helium and carbon nuclei. In both cases hydrogen atoms are used up, radiant energy is given out, and helium atoms are formed. It is in this sense that we can think of hydrogen as the atomic "fuel" that is constantly being used up and of helium as atomic "ashes" that are left over after energy has been generated.

The increase in helium, considered along with the speed of rotation of a star, has an important effect on a star's future. If a star rotates quickly most of its material stands a good chance of being stirred up and mixed well together. Thus the hydrogen in the outer part will circulate to the inner regions and replace some of that used up in generating the star's energy, while some of the helium "ash" in the interior is pushed outward. On the other hand, in a slowly rotating star like the Sun there will be far less mixing of material and the helium tends to pile up near the star's center.

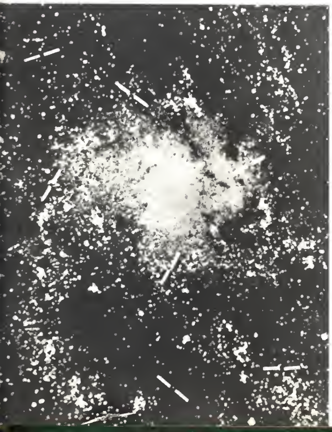
This concentration of helium "ash" has an important effect on what happens inside a slowly rotating star. Because helium atoms are heavier than hydrogen atoms they tend to block the passage of energy from the center to the star's surface. In other words helium is more opaque to radiation than hydrogen. As a result, the central core of the star will gradually become more and more opaque to radiation. This means that much of the energy produced there will not quickly be able to find its way outward. The center of the star will heat up and this will increase the rate of nuclear reactions. Then, as the radiation does eventually reach the surface, the surface will heat up too. Gradually the star becomes hotter and moves *up* the main sequence. Beginning probably as an M-type star it gradually moves up to K, then to G, then to F.

This seems to be the course that the great majority of stars take as they grow older, and it is a very different course from the one that Henry Norris Russell guessed at when he first tried to draw conclusions from the Hertzsprung-Russell diagram. We saw earlier that he imagined that stars would begin as O- or B-types and then move *down* the main sequence toward class M. The reason for the difference is that in guessing at a movement down the sequence, Russell and other astronomers working in the early 1900s could not know about nuclear reactions, nor did they take into account the fact that helium is rather opaque to radiation and causes a star to heat up rather than cool down. Today astrophysicists believe that the Sun has moved upward along the main sequence. They believe that it began life as an M-type dwarf more than 4000 million years ago. Since that time it has gradually become hotter and hotter, moving up the sequence first to K and then to G, where it is today, and where it seems to have been for at least 500 million years.

It is not very difficult to understand why a star moves up the spectral sequence from M to K to G to F. But what happens next? When a star reaches the F stage of its existence the temperature near its center climbs to something more than 20 million degrees, and at that temperature the atomic



Cepheid variables undergo a regular change in brightness. In these photographs of the same group of stars, taken at different times, marked Cepheids vary in brightness.



reactions that produce its energy undergo a vital change. Instead of building up most of its helium from hydrogen, the star now begins to build up helium from hydrogen and carbon. This second kind of reaction, called the *carbon cycle*, uses up hydrogen very rapidly. So the future course of the star will now depend both upon the hydrogen supplies available and also upon the extent to which helium accumulates in the star's central region. And this second point depends on the star's speed of rotation.

Astrophysicists have now come to the conclusion that after a star has reached the F class there are probably two quite different ways in which it might evolve further. If it is rotating rapidly, some of the helium will be removed from the central region and circulated farther out. What is more, hydrogen from the outer parts will be brought toward the central core where nuclear reactions take place. A star of this sort will go on increasing in brightness until it reaches type A.

On the other hand, if the star is rotating rather slowly, like the Sun, the carbon cycle will cause a fast burning up of hydrogen in the central parts and a speedy increase in the amount of helium. Some of the energy generated will continue to escape to the outer parts of the star, and the central parts will reach a steady temperature and stay there. More hydrogen will be consumed and, in due course, the central parts will shrink. At the same time as this shrinking occurs, the outer parts of the star will begin to expand. Its radiation will now be reaching us from an immense surface with a not very high temperature. In other words the star will have become a red giant. As time passes less and less hydrogen is available and the whole star begins to contract once more.

At the red-giant stage other reactions, which can take place at lower temperatures, take over, and helium is then built up when hydrogen reacts with atoms of beryllium, boron, and lithium. Because the star is rotating slowly and its elements are not well mixed, these reactions do not go on at a steady pace. As a result the star may vary

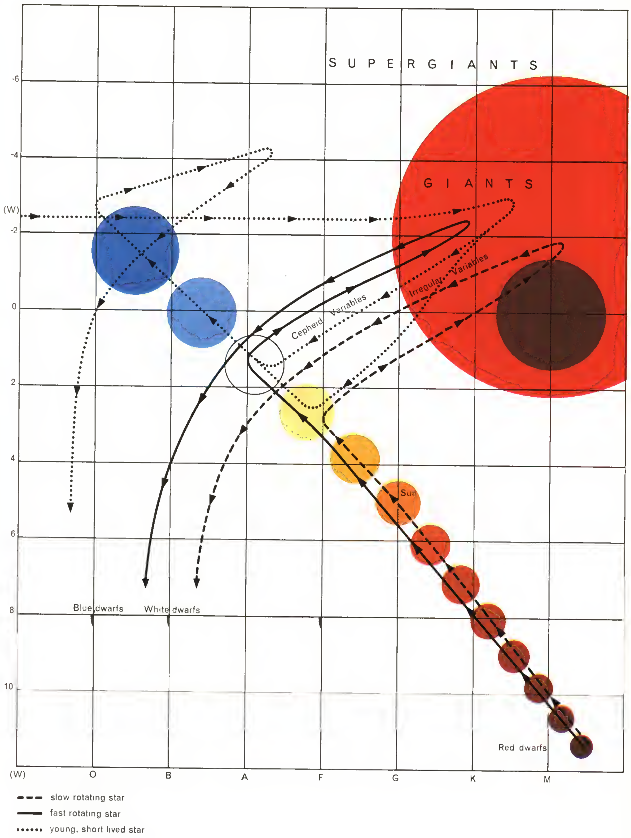
in brightness from time to time and become one of the stars we call *variables*. Most variables take from three months to two years to complete a cycle from bright to dim to bright again, and such stars are classed as *long-period variables*. As more and more hydrogen is used up, the star's radiation may become even more erratic, and a cycle from bright to dim to bright again may then take only a few hours or so. These *short-period variables* are known as *Cepheids* because the first variable with so short a period was discovered in the constellation of Cepheus. There are other short-period variables, called *RR Lyrae*, which we shall meet in the next chapter. As a red giant grows still older it may become an RR Lyrae variable rather than a Cepheid.

So far our slowly rotating star has had a very checkered life. After moving up in the main sequence from M to F it became first a red giant and probably a long-period variable as well. Then it shrank to a smaller, more rapidly variable, but still reasonably bright star. By comparison our star with a rapid rate of rotation has so far had an uneventful life, climbing sedately up the main sequence from M to K, to G, to F, to A. Yet after it reaches A, helium ash will probably cause it to move into the red-giant region. What happens next? By now both kinds of star have used up most of their hydrogen and are nearing the closing stages of their life. Can we say exactly what these are? Although we cannot be certain, astrophysicists believe that they can narrow things down to three possible answers. One is that the star, having used up almost all its hydrogen, begins to shrink very rapidly. This happens because there is no longer enough radiation being produced inside the star to give an outward pressure equal to the inward pull of gravity. The star now begins to collapse inward on itself. At this stage the central regions are composed of the nuclei of helium and other atoms all packed closely together. In these circumstances radiation at the star's center cannot escape to the surface. Only the radiation generated near the surface itself is emitted into space. The star is now a dense, relatively dim, but quite massive body whose light will be white or even bluish. It has become a white dwarf and occupies a position in the lower central region of the Hertzsprung-Russell diagram.

The second possibility is that the star continues to become dimmer and to shrink until it ceases to shine altogether. The center parts are now composed of tightly packed broken atomic material—"degenerate matter"—with no power to emit radiation. The star is, to all intents and purposes, dead. White dwarfs probably end their lives this way also. There is still a third possibility. Suppose that we have an aging star that is shrinking and whose materials are very poorly mixed. Then for some reason an abundance of hydrogen suddenly reaches the central parts. When this happens the star's radiation undergoes a terrific increase, and the force of radiation pressure blows off a great globe of very hot, bright gas. Such an exploding star suddenly increases immensely in brightness. If the brightness increases 10,000 times (10 magnitudes) the star is called a *nova* or new star. This is because it was probably too dim to be seen without a telescope before the explosion, and may now appear as a bright new star in the night sky. If the explosion is so exceptional that the brightness of the star becomes quite fantastic, the star is called a *supernova*. While a nova may suddenly become anything from 10,000 to 160,000 times as bright as the Sun, a supernova may outshine the Sun by 10 *million* times or more.

A supernova seems to indicate a complete explosion of a great part of a star's material, but such explosions are rare. In the last

This diagram is plotted on a grid like that used for the Hertzsprung-Russell diagram on page 91. By following the arrows on the various lines we can see how astrophysicists believe three different kinds of star to vary in brightness and temperature as they age. (The higher up the brighter, the farther left the hotter.)



SUPERGIANTS
GIANTS
-6
-4
(W)
-2
0
2
4
6
8
10
Irregular Variables
Cepheid Variables
Sun
Blue dwarfs
White dwarfs
Red dwarfs
(W)
O
B
A
F
G
K
M
slow rotating star
fast rotating star
young, short lived star

If an abundance of hydrogen suddenly reaches the center of an aging star it may cause a violent explosion. Such a rare supernova explosion occurred in A.D. 1054. It produced the Crab Nebula, a vast and still expanding patch of gas.

A nova explosion involves only the outer regions of a star and is less violent. Below are three photographs of Nova Aquilae that increased greatly in brightness in the year 1918. They show how its shell of gas looked in 1922, 1926, and 1931.

thousand years only three have been observed in our own Galaxy. The earliest, that of A.D. 1054, is now invisible to the naked eye, and in the telescope it is seen only as a patch of expanding gas. It is known as the Crab Nebula. A second supernova appeared in the constellation Cassiopeia in 1572, and a third appeared in Ophiuchus in 1604. Novae are less rare; since 1918 several have, for a period, become visible to the naked eye. None of them can now be seen without a telescope. After a supernova explosion a star shrinks, until, with all its energy used up and its center a mass of degenerate matter, it "dies." But after a nova explosion, which involves only the star's outer shell of gas, a star merely drops in brightness. It may have enough material left to burst forth again in the same way at some later time.

So far we have traced the life story of stars from type M to type F and then either to A on the main sequence or else to the red-giant or white-dwarf stages. We have also seen how stars may end their lives. But we have not yet come across any stars of type O or B. Why? Are they different from the other stars? Astrophysicists believe that they are, and that these stars are very young, and are made of well-mixed material that radiates away at an immense rate. Such stars are massive, and they are believed to have a dense central core and a huge atmosphere that is radiating brightly as if the star has a gas cloud surrounding it. They certainly show a spectrum that clearly indicates a bright shell of gas surrounding a hot central core. Some stars of this kind have so exceptional a shell that their spectra are composed mainly of bright lines produced by glowing gas. These stars were first recognized in 1867 by two French astronomers, G. Wolf and G. Rayet, and they are called Wolf-Rayet stars. (They are sometimes also classified as W. stars.) These stars, whose life is probably 10 times shorter than that of the Sun, may begin as huge collections of gas and then shrink rapidly into red giants. The carbon cycle may not start in these stars until the red-giant phase is ended. This would mean that they next enter the main sequence high up, at type A or F. Then, pouring out energy in vast quantities, they move up from A to B and then to O. At this stage they shine with a bright blue light and have very high surface temperatures: They become supergiants. It is only after they go through this stage that they contract, begin to dim, and eventually die. So it seems that in order to reach the upper parts of the main sequence a star must enter it some way up, at A, F, or even G.

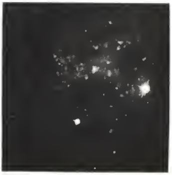
Astiophysicists are still not certain that these ideas about the life history of stars are correct. Yet there is this to be said for them. They do at least fit all the various kinds of stars we observe into one complete scheme, using nuclear reactions to explain how the stars produce their radiation and how they change as they grow older. They also make sense of the relationship between the mass of a star and its brightness.

These time exposures show how after blazing out brightly a remote supernova gradually became too faint to observe.

August 23, 1937

November 24, 1938

January 19, 1942



The Birth of Stars

There is still one important question we have not asked. Where do stars come from in the first place? How is a star born? Again, no one is certain of the answer, but it seems likely that stars must be formed out of the gas that exists in a galaxy. In the first chapter we saw that most of this gas can be observed in the form of enormous clouds called nebulae, some being dark and others bright and glowing—all of them extending over large areas. The gas, which is spread out thinly, is set glowing by radiation from O- and B-type stars embedded in it, and we have just seen that these stars are young ones. This may mean that young stars are in some way associated with nebulae. The nebulae in Cygnus and Sagittarius are good examples.

A careful study of photographs of fairly nearby nebulae, such as the magnificent one in the "sword" of Orion, shows that they contain many dark "lumps" of more tightly packed gas. Some astrophysicists believe that these are supergiant stars actually in the process of being formed. Possibly, then, the O and B stars in the nebula were also formed in this way. At first they would take shape as dense patches, then as dark globes of gas packing itself more and more tightly around the central core. When they had shrunk sufficiently to crush their central atoms together so that the carbon cycle of radiation started, they would begin to glow as stars. As they grew brighter they would then set the nebula itself glowing by their great outpouring of radiation. This, then, may be the way in which giant and supergiant stars form. But what of the other stars? Are they formed in a similar way?

On the left we see the Lagoon Nebula in Sagittarius. On the right is the Veil Nebula in Cygnus. Both show bright areas of gas that is set glowing by radiation from young O- and B-type stars. It is probably in the dust and gas of nebulae that most new stars are born.

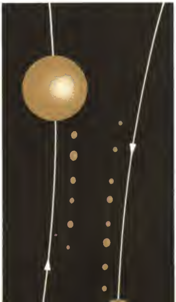
The most likely "breeding ground" for the more normal stars, such as our Sun, lies in the gas that, spread out between the stars, stretches right through our Galaxy. This gas is composed mainly of hydrogen, plus other light elements, and is so thinly spread that on the average it contains no more than about 16 atoms per cubic inch, compared with thousands upon thousands of millions per cubic inch in, say, a lump of sugar. However, our Galaxy contains such countless billions of cubic inches that the total number of atoms would provide enough material to form millions of stars. As we might expect, this gas is not distributed evenly within the Galaxy. In some places it forms the fairly dense patches we call nebulae; in other places it is so thinly spread out that we cannot see it, and know of its existence only by the radio waves it sends out—waves that can be picked up by radio telescopes.

Besides this interstellar gas, there is also interstellar "dust" in our Galaxy. This dust is nowhere near as great in quantity as the gas, and what it is made of is still something of a mystery. It may contain crystals of ice and possibly other substances as well. At any rate, most of the dust particles are small, but some of them may measure a few yards across. These dust particles produce two effects that we can observe on Earth. First they scatter blue light and so make distant stars appear redder than they really are, just as dust in our atmosphere often makes the Sun appear like a red globe in the sky. Second, the clouds of dust can often be seen as dark nebulae in the Milky Way. (Examples are the famous Horsehead Nebula and the Coal Sack Nebula.) This shows that interstellar dust, like interstellar gas, is not evenly spread out in space.

So both dust and gas are more concentrated at some places than at others, and astrophysicists believe that it is in these concentrated regions that most stars are first formed. Our own star, the Sun, was probably formed through just such a process of gas collecting into a globe, heating, and eventually emitting radiation through nuclear reactions.

Around the Sun, nine planets and a host of asteroids are perpetually orbiting. We must now ask if these bodies were also formed out of interstellar gas and dust in a way similar to the stars. Some astrophysicists believe that the Solar System was drawn out of the Sun's own material after it had become a star. Others think that the planets condensed out of smaller amounts of gas and interstellar dust "left over" when the Sun was formed. However, both ideas accept as a fact that the Sun formed before the planets.

Some attempts to explain how the Sun and the planets were formed involve an "intruder" star. Some scientists have suggested that a second star approached very close to the Sun, grazing it as it passed by. Others have suggested a collision with some other star. In either case great quantities of gas would have been freed. This would have



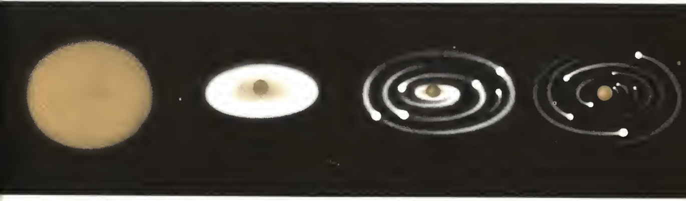
Some astronomers believe that the planets are the result of some catastrophe. One idea is that another star grazed the Sun in passing. The strong pull of gravity tore material away from both, and out of this the planets may have condensed. Other astronomers think that as the Sun took shape from a swirling cloud of gas and dust its own rotation caused it to throw off material. This would evaporate, move outward, cool, and condense to form planets.

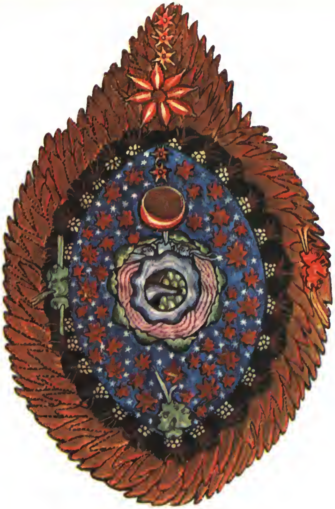
formed into giant "drops" that eventually condensed and became the planets.

Another theory is that the Sun and some other star once formed a binary system. A nova explosion of the Sun's companion might have broken up the binary system, and the planets could have formed out of some of the gas that remained behind with the Sun. Or, again, the Sun's companion could have collided with yet another star. In that case, too, enough gaseous debris would have been left behind to form the planets.

These theories all suppose that the Sun underwent some great catastrophe, such as a collision, or at least that it was close by when such a thing occurred. Yet an increasing number of astrophysicists prefer the idea that the planets and the Sun condensed out of the same mass of interstellar dust and gas. The details of exactly what may have happened are complicated, and it is not necessary for us to try to master all of them. The theory depends mainly on two things: 1. the radiation that the newly formed Sun gave out; 2. the fact that tiny lumps of ice and solid ammonia could act as centers around which material thrown out from the Sun could build up into dense atoms by nuclear reactions. This theory has enabled astrophysicists to explain why different planets lying at different distances away from the Sun are built up of different materials. It also provides an explanation of how the molecules that go to make up living things were gradually formed.

Whatever the true explanation of the formation of stars and planets may turn out to be, the general idea that stars develop from interstellar dust and gas and that the planets of the Solar System could not form without the Sun being present seems sound enough. We know for certain that interstellar gas and dust are contained within our own Galaxy, and when we study other galaxies remote from our own we can detect that many of them also have their own gas and dust as well as stars. Where we believe this gas and dust came from, and the way we think the galaxies themselves are formed, depend upon our picture of the whole universe.





St. Hildegard made this pear-shaped picture of the universe about 800 years ago. At the center is the Earth. Around it are the stars and above it is the Moon. Beyond the Moon come first the inner planets, then the Sun, and lastly the outer planets. In fact the universe is so vast that we no longer compare its distances with those of the Sun, planets, and stars. Instead we think of the distances between galaxies. The galaxy in Sculptor, shown opposite, is one of many that are millions of times farther away than the farthest star we can see.

5 Theories of the Universe

Without a telescope we can never see more than a very small section of our own Galaxy. With large optical and radio telescopes it is possible to observe thousands of galaxies, some so far away that the figures expressing their distances are meaningless to most of us. Even so, astronomers have penetrated only a short way into the whole universe. The universe is so vast that we simply cannot form any ideas about its size and layout by making comparisons with the sizes of stars and the distances between them. The stars are far too small and insignificant. We must think instead of whole galaxies and the distances between them.

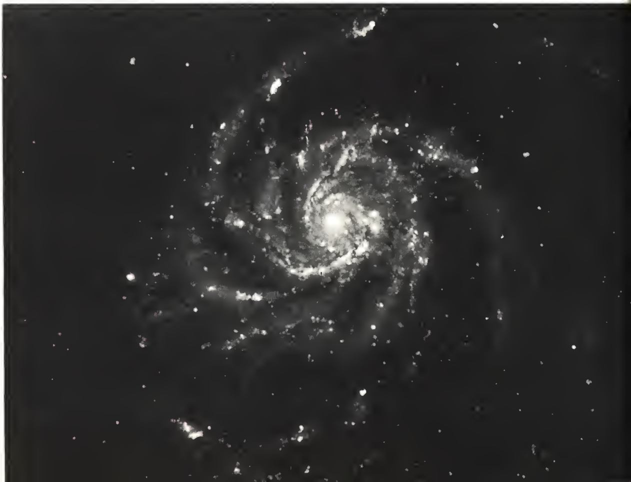
Fortunately many galaxies—especially the nearer ones—can be photographed. And as we saw in earlier chapters, we can learn rather a lot about them: their distances, the kinds of stars they contain, and the speeds at which each galaxy is moving away from us. Let us now look in more detail at these vast collections of stars to see what they can tell us about the universe as a whole.

Galaxies seem to be of two main kinds—*elliptical* and *spiral*. The spirals have a dense globe-shaped central part (the nucleus) and arms winding around it in a spiral fashion. They are rather like giant pin wheels, or catherine wheels. Elliptical galaxies, on the other hand, do not have spiral arms. They also differ from spirals in another way. They seem to be free from dust and gas, or at least they contain very little. Spirals differ considerably in size, but an average one may contain material amounting to something like 2000 million times the mass of the Sun. Much of this material is contained in the stars of the galaxy, but part of it consists of gas and dust spread out among the stars, the amount of gas being about nine times that of the dust.

Our Galaxy is a spiral, and we saw in the first chapter that it rotates. Other spirals rotate in a similar way, with the outer parts moving far more slowly than the dense group of stars at the center. For example, in the Andromeda Galaxy the cluster of stars forming the inner part of the nucleus rotates once every half million years, and the outer parts of the nucleus rotate once every 20 million years. The outer portions of the spiral arms are so distant from the nucleus that their rotation periods must be measured in hundreds of millions of years.

At first sight we might think it would be easy to decide which way a spiral galaxy is rotating, and whether or not the arms trail behind the direction of spin, but in fact it is usually very difficult. We can see why if we think of three spiral galaxies lying in different positions so that we see each of them from a different angle. We look straight up at the first one and see it spread out in the sky like a catherine wheel; the second one is seen edge-on; and the third one is seen from such an angle that it seems tilted toward us.

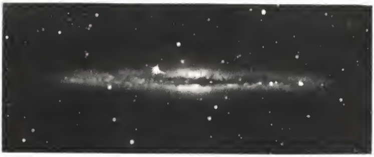
The first one gives us no clue whatever about its direction of rotation. Although we see its arms spiraled out into space, we cannot detect any motion. To do so we should have to watch it rotate part way around. But since this would take a quarter of a million years or longer to notice, man obviously has



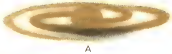
not yet had time to make the necessary observations. The second one, which we see edge-on, is more promising. We can tell which way it rotates by observing it with a spectrograph and measuring the shift of its spectral lines (see page 54). But because we see it edge-on we have no way of telling which way the spiral arms lie. So although we know which way the galaxy is rotating we do not know whether the arms are trailing behind the direction of spin or moving ahead of it. In theory they could be doing either.

Our only chance of getting all the information we need comes from the third galaxy—the one that seems tilted toward us. We can observe it with a spectrograph and find out which way it is rotating, and in this case we can also see the arms. Even so, before we can tell whether or not the arms are trailing behind the direction of spin, we must find out which way the galaxy is tilted toward us. This is not easy to do, but the problem has been solved for about a dozen spiral galaxies by observing the dust belt that lies across their centers. Because dust blots out light from behind, we know that the dust belt must lie across the side of the galaxy that is nearer to us. In our diagram we can see that side A is therefore closest to us and that the arms must be trailing. This is, in fact, true of all the galaxies that have been observed in this way. Since the arms of spiral galaxies trail, there is a tendency for them gradually to wrap themselves around the nucleus.

Spiral galaxies seem to vary considerably in size. Some of the smaller ones appear to be 30,000 light-years in diameter, while the larger ones have diameters of about 120,000 light-years. On this scale the Milky Way, with a diameter of about 100,000 light-years, is a large galaxy. They also vary in brightness according to the number of stars and bright nebulae they contain. According to measurements we are able to make, the absolute magnitudes of most spiral galaxies range from –15 to –19. We can get some idea of what this means by imagining how bright the Andromeda Galaxy would appear if it were "only" 33 light-years away from us —somewhere between the distance of the



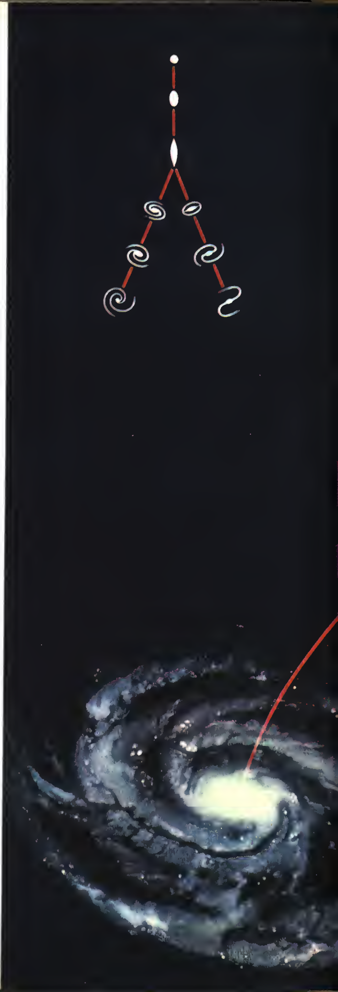
One of the two main classes of galaxies are the spirals, and astronomers need to study their motions. The one on the left, NGC 5457, is seen face-on, like a catherine wheel. So slowly does it rotate that we cannot even observe which way it turns. The top one on the right, NGC 891, is seen edge-on. Shifts of spectrum lines tell us which way it is turning, but we cannot see the arms to tell whether they trail or move ahead. The last, NGC 7331, is seen at an angle. We can tell the way it turns and we can also see the arms. But to learn whether or not the arms are trailing we have to know, from obscuring dust, which side of the galaxy is nearer to us. In the diagram side A is the nearer one, and we know the arms are trailing.



stars Vega and Arcturus. At that distance it would be 600 times brighter than the full Moon! So it is clear that spiral galaxies are very bright objects in space, even though they seem dim to us because of their great distances.

Photographs of spirals show many variations, and astronomers have divided them into two main groups—*spirals* and *barred spirals*. In the ordinary type of spiral, such as our own Galaxy and the Andromeda Galaxy, the nucleus is round or oval shaped, but a barred spiral has a nucleus that extends far outward so that it looks just like a long bar. Astronomers have also divided up each of these two main groups into three subgroups —*a*, *b*, and *c*. Group *a* contains galaxies whose spiral arms. are wound very tightly about the nucleus. Group *b* spirals have arms that are rather more spread out (as in the Andromeda Galaxy and our own). Group *c* spirals have arms widely spread out from the nucleus. If we label ordinary spirals *S* and barred spirals *SB*, we can refer to the various subgroups as *Sa* or *SBa*, *Sb* or *SBb*, *Sc* or *SBc*. The Andromeda Galaxy is classified as an *Sb*, whereas the very open catherine wheel in Ursa Major (the Great Bear) is of type *Sc*, and the barred spiral in the constellation Eridanus is of type *SBb*.

Elliptical galaxies appear to be without arms at all. In fact they seem to have no very definite "edge" of any kind and they are without noticeable amounts of dust or gas. They are clearly different from the spirals



Here pictures and a diagram explain how the galaxies are classified. Along the handle of the fork are ellipticals, ranging from globe-shaped (E0) at the top to thin ovals (E7) at the bottom. Along the left prong are spirals. They range from those with tightly wound arms (Sa) at the top to those with loosely wound arms (Sc) at the bottom. Barred spirals (right prong) range from SBa at top to SBc at bottom.

in still other ways. Ellipticals vary in shape; some are round and globelike while others are certainly very oval or elliptical. The most rounded globular ones are referred to as type E0 galaxies, and the most oval ones as type E7. The numbers between 0 and 7 indicate how globular or how elliptical any particular one is. The limit of ovalness at E7 is really no more than a chance happening. Astronomers began with the idea that as they examined more and more galaxies they would eventually find ellipticals so flattened that they would merge into the spiral range, and they could, of course, add extra numbers beyond 7 to describe such galaxies. But this has not been necessary and no galaxy more oval and flattened than type E7 has ever been observed.

The difference between types E0, E1, E2, and so on, is now known to be more than a mere difference of shape. Studies of the spectra of elliptical galaxies show that the more oval they are, the faster they are rotating. Seen by eye through a telescope, elliptical galaxies appear smaller than spirals. But when a time exposure is made of them, and the photographic plates are carefully examined with a microphotometer, it becomes clear that they stretch farther out into space than appears to the eye alone. The results of measurements of this kind show that elliptical galaxies seem to be similar in size to the spirals but not quite as bright.

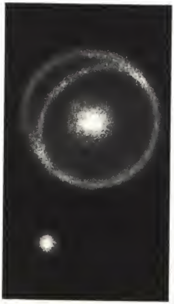
During the past two hundred years various astronomers have made catalogues of nebulae and galaxies. The first to do so was the Frenchman Charles Messier. Messier made his catalogue, which was published in 1784, so that he would not confuse the hazy nebulous patches and the hazy-looking galaxies with comets, for a comet also looks no more than a hazy, irregular patch of light if we observe it in a telescope before it has formed a tail. The first catalogue listed the positions of 53 nebulae and 50 galaxies, and each of them was given its own catalogue number from 1 to 103. Many of the brighter galaxies are still referred to by their *Messier number* —M 31 for the Andromeda Galaxy, M 101 for the Sc spiral in Ursa Major, and so on. In the hundred years that followed the publication of Messier's catalogue, other catalogues were made, one by Sir William Herschel, the discoverer of the planet Uranus, and his son Sir John Herschel. In 1890 these two catalogues, together with lists prepared by other astronomers, were all combined by J. L. E. Dreyer in what is known as the *New General Catalogue*. Galaxies listed in this are given an NGC number. This means that certain galaxies have both an M number and an NGC number. The Andromeda Galaxy, for example, can be referred to either as M 31 or as NGC 224. The New General Catalogue lists many more galaxies than Messier did, and even this list has been added to by the later publication of two *Index Catalogues*, which gave rise to IC numbers.

Altogether more than 12,000 galaxies have been listed, and some of them have

Charles Messier

Sir John Herschel

J. L. E. Dreyer



On the left are three of the men who made early catalogues of nebulae. The distinction between galaxies and masses of hot gas was not then easy to make. Above is an early drawing of the Crab Nebula (glowing gas). On the right are drawings of Messier 51 (the Whirlpool Galaxy shown on page 25). The first was made in the 1830s and the second some 20 years later.

three different numbers: M, NGC, and IC. Yet this has nowhere near exhausted the total of all those observed. If we examine these catalogues we find that they list far more spiral galaxies than ellipticals. But this does not necessarily mean that ellipticals are actually less common than spirals. The elliptical galaxies are dimmer than the spirals, and it may well be that we see fewer of them simply because they are too dim to see, especially those in the more distant parts of space.

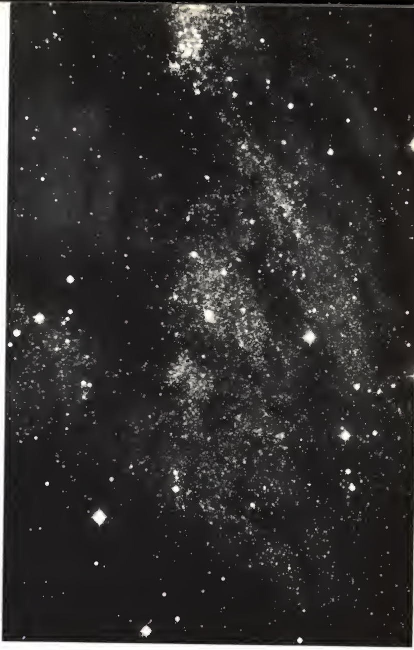
Besides elliptical and spiral galaxies there is a third type, which is rare except among very small galaxies. This kind appears to have no regular shape, no proper structure, and, more often than not, no nucleus. Galaxies of this kind are called *irregulars*, and all galaxies that cannot be classed either as elliptical or spiral are referred to in this way. So far as the larger galaxies are concerned, they amount to only two or three per cent of all those observed. The two best-known galaxies of this kind are the Magellanic Clouds, although some astronomers prefer to regard them as barred spirals. Even though the exact classification of the Magellanic Clouds may be open to question, they certainly appear irregular in outline and look very much as if they were pieces broken off the Milky Way.

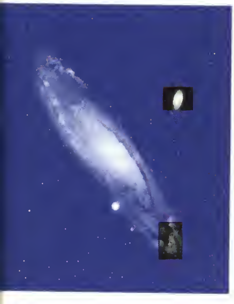
As a result of their studies of galaxies, including the Milky Way, astrophysicists group all of the stars into two categories—*Population I* and *Population II*. Population I includes the bright and bluish O-type and B-type stars, such as those making up open clusters like the Pleiades and the Hyades, and all those stellar bodies, *including* interstellar dust, that are found in the spiral arms of S and SB galaxies. Population II includes all the different kinds of stars found in the nuclei of both elliptical and spiral galaxies and also in the globular star clusters that surround the spiral types. These "populations" were first proposed by the American astronomer Walter Baade after he had examined photographs of galaxies taken with the 200-inch Palomar reflector. Population II does not have any very bright blue or blue-white stars, and the giants it does contain are red. In Population I just the opposite is true, the brightest stars being blue and blue-white giants and supergiants.

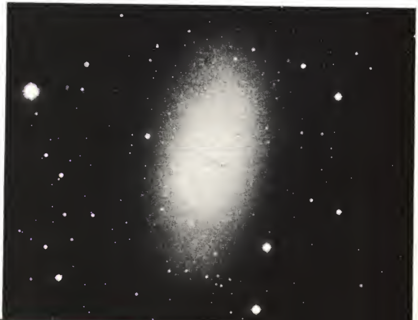
According to our life history of stars in the previous chapter, we found that the O and B giants and supergiants are probably young stars that are using up their hydrogen quickly. We also came to the conclusion that the red-giant stage in a star's life could well be a sign of old age. If these ideas are correct, Population I contains the young stars (O and B giants and supergiants) and Population II contains the old stars (red giants). Not only is there a complete lack of young stars in Population II, but there is no interstellar dust, which is the material from which stars are born, lying around them. All this evidence supports the idea that Population II stars are much older than Population I stars.

Beside elliptical and spiral galaxies there is a third type, called the *irregulars*. Here is one of them, NGC 520. Less than one in 30 of the large galaxies are of this type, but with minor galaxies the proportion is much higher.

Below is a photograph of the Andromeda Galaxy (NGC 224) and its companion, NGC 205. On the right, part of one of Andromeda's spiral arms is shown in more detail. Here we find Population I stars. These include young O- and B-type stars and dust, but no very old stars such as red giants.







Here is a more detailed view of the second marked area in the photograph above. In this area are Population II stars. These include the older types of star found in elliptical galaxies and in the nuclei of spirals, but not the younger stars found in spiral arms. (Big white spots in both these photographs show "foreground" stars of our own Galaxy.)

Ellipticals, with no young stars, may represent a galaxy in old age. Maybe the trailing arms of spirals wind themselves into the nucleus, leaving a fast-rotating oval like the E7 (first picture). As the galaxy ages more, its rate of rotation slows down. In time it becomes less oval, like the E5, and finally quite globular, like the E0.

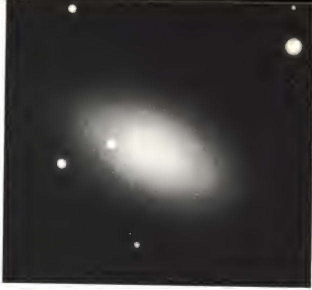
The Life and Death of Galaxies

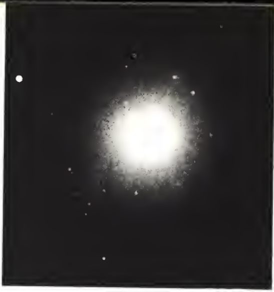
The idea that the two populations of stars are different in age is very important when we come to consider how the galaxies themselves were formed and how they have evolved. Which, for example, came first, the spirals or the ellipticals? Until Baade's discovery of Populations I and II, most astrophysicists thought that galaxies began as globe-shaped ellipticals (E0) and then gradually changed through E1 to E7 as they aged, after which they became either S or SB spirals. Since Baade's discovery, the picture has had to be changed. This is because the only galaxies with dust, gas, and young O- and B-type stars among their arms are the spirals. And it must follow that the galaxies containing the young stars are the young galaxies. In other words, the spirals and barred spirals are younger than the ellipticals, not older.

The new picture of the life history of a galaxy is that it begins as an uneven mass of rotating gas, dust, and later of stars also. As it goes on rotating, new stars continue to form in the outer regions of the galaxy. This is why most of the O- and B-type giants and supergiants are observed in the spiral arms. As the spiral—whether it is a regular S type, or a barred SB type—continues to rotate with its arms trailing behind, the arms gradually become more and more closely wrapped around the nucleus. In this way the galaxy progresses from an Sc or SBc type, with loosely wrapped arms, to the next stage, with somewhat more tightly wrapped arms, which is Sb or SBb. Continued rotation of the galaxy makes the spiral arms close up still further, increasing the size of the nucleus still more, and we then have a galaxy of type Sa or SBa.

By the time this stage is reached most of the O and B giants and supergiants will have used up their hydrogen and turned into dimmer stars. The stars still shining will be older, and the galaxy will be on its way to becoming a collection of Population II stars. By the time the arms have become completely wound into the central parts, an oval nucleus will be all that remains of the original galaxy. This oval nucleus will still be rotating fairly rapidly, but the galaxy will now have become a type E7 elliptical. As it continues to age, its rate of rotation steadily slows down and it becomes more and more rounded in shape. Finally it becomes a completely globular E0-type galaxy. But what happens next? No one knows and no generally accepted explanation is yet available. All we can say is that probably the stars, and so the E0 galaxies that contain them, age until the stars become degenerate and the galaxies collapse into dense, broken-down matter.

Not all astrophysicists agree on this picture of the life story of a galaxy. Some do not believe that galaxies evolve at all. They think that the different types we observe were different right from the time they were formed. The real difficulty, of course, is that we have not enough evidence to be certain.





At the present, however, that evidence seems to point to a galaxy beginning its life as an open spiral and ending as a globular-shaped elliptical. But, we may well ask, where did the original material of the galaxy come from in the first place? How did the galaxy's life as an open spiral begin? Here again, astronomers have no definite answers, but by examining the distances and motions of the galaxies we can obtain some idea of what the "beginning" of the universe may have been like and make some guesses about what may happen to it in the future. But at this stage of our knowledge it can be guess-work only!

To begin to tackle these problems we must start by asking how far away the galaxies are. In the third chapter we found that by using the diameter of the Earth's orbit as the base line of a triangle we could measure the distance of the stars up to about 325 light-years away. Because the galaxies lie at distances much greater than this we must turn to a different method of measurement. Cepheid-type variable stars, many of which are bright enough to be picked out in other galaxies, serve as our yardstick. Cepheid variables, as we saw in the last chapter, take their name from the star δ (delta) Cephei and have a short and regular period of variation in the amount of light they give out. The important thing about them, so far as measuring the distance of galaxies is concerned, is that there is a definite relationship between their period of variation and their absolute magnitude. The shorter the period a Cepheid has, the dimmer it is. For example, the Pole Star, with a period of 3 days 22 hours, is dimmer than δ Cephei with a period of 5 days 9 hours, and δ Cephei itself is dimmer than β (beta) Doradus, which takes 9 days 20 hours to complete its cycle from brightest to dimmest back to brightest again. All of this means that if we observe the speed of variation of a Cepheid, we can tell its absolute magnitude. If next we measure its *apparent* brightness we can work out how far away from us it is.

Because Cepheids are visible in the nearer galaxies, we can tell the distances of those galaxies by fairly straightforward observations. Even so, recent studies of variable stars, developed by Walter Baade in the United States and Andrew Thackeray in South Africa, have shown that our estimates of distance for these galaxies need revising, and that they are at least twice as far away as astronomers formerly supposed.

The reason for this change is that Baade and Thackeray have found that the old brightness and period-of-variation scale of the Cepheids made nonsense of their observations of other short-period variables that differ from the Cepheids in one very important way. These stars, called RR Lyrae variables, are dimmer for their short periods of variation than the Cepheids are. For instance, an RR Lyrae with the same period of variation as a short-period Cepheid, say of half a day, would be about one and a half

times dimmer. Now when observations of the Andromeda Galaxy (M 31) were made, no RR Lyrae variables were visible although, even if they are dimmer than Cepheids, they should have been seen if M 31's distance were only three quarters of a million light-years as was believed. By taking this into account, as well as observations made of RR Lyrae variables in the Magellanic Clouds, Baade and Thackeray showed that the old estimates of the distance of M 31 and of other galaxies must be increased.

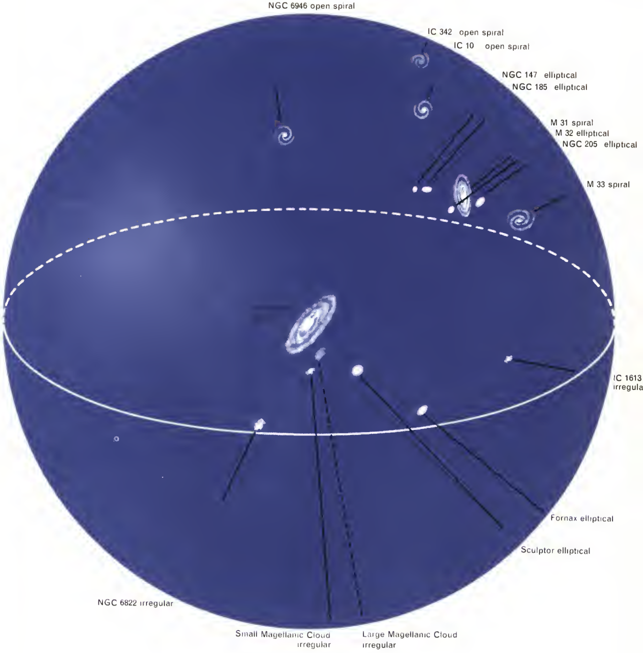
Many galaxies are so far away that we cannot possibly pick out their individual Cepheids, even with the 200-inch Palomar reflector. For these galaxies we have to rely on yet another system of measurement. Here we can use a still brighter kind of star that can sometimes be picked out even in very distant galaxies—the O-type supergiant. We know that the true brightness or absolute magnitude of such a star is around –5. If we can measure its apparent magnitude we can then work out its distance. However, this method can be applied only to spirals, since elliptical galaxies do not contain O-type supergiants, and in any case the method is not really very accurate. The only really universal method of measuring the distances of all kinds of very distant galaxies is to suppose that one galaxy of a particular type radiates as much light as every other galaxy of that type. If we assume that all galaxies of the same type have the same true brightness, it is clear that the one that appears brightest will be the one nearest to us, while those that appear dimmest will be farthest away. This method of measuring will not, of course, give accurate results in every case, because some galaxies of a given type may be smaller than others. This means that they will also not be quite so bright as we have assumed. Nevertheless, this method does, by and large, give a fair indication of distance. A similar method is also used by radio astronomers who measure the radiation received at certain radio wave lengths. In this way they obtain a scale of distance that they can compare with the scale used by astronomers working with optical telescopes.

The Plan of the Universe

By making use of all these measuring systems, astronomers can not only tell how far away various galaxies are from us, but also how far away they are from each other. As it turns out, more than half of them appear to be congregated in clusters. Our own Galaxy is a member of what is called the *Local Group*, a collection of at least 13 galaxies. It is possible that this should be increased to include certain open spirals, but the distances of these galaxies are so uncertain that most astronomers exclude them from the Local Group. As it now stands, the group contains three spirals, four irregulars (including the two Magellanic Clouds), and six ellipticals. The whole collection forms a flattened oval about 600,000 light-years thick, two million light-years across, and something like four million light-years in length. The Andromeda Galaxy lies near the middle of the oval, while our own Galaxy and the Magellanic Clouds are at one end. (Our plan shows a different angle.)

Among the clusters "near" to the Local Group is one that lies about 40 million light-years away in the constellation Virgo. One of the most distant groups yet photographed is 3c–295 in the constellation Boötes. It lies at the immense distance of 3500 million light-years away from us. But even this does not bring us anywhere near the limits of the universe, for radio astronomers have traced galaxies half as far away again.

Astronomers and astrophysicists have also learned something about the immense space that lies between one galaxy and its nearest neighbors. They know, for instance, that this intergalactic space contains some very thinly spread out material and here and there they have observed "stray" stars. Also, the outermost regions of some of the galaxies forming a cluster appear to overlap and mingle. Perhaps most exciting of all is the fact that one or two photographs have revealed bright lanes of some kind of material lying between widely separated galaxies. These lanes offer quite definite proof that, whatever else it may be, intergalactic space is certainly not empty, as it was once thought to be.



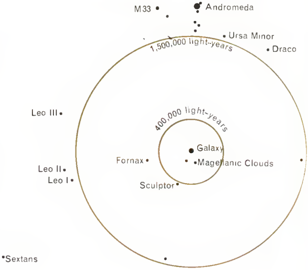
Galaxies are not all spaced evenly apart. More often they are found in clusters. Here is a plan of the *Local Group*, the cluster containing our Galaxy. It has at least 13 members.

More are shown but some are of uncertain distance and may actually lie beyond. This view is somewhat like a glass ball. Dotted lines show far side, full lines near side.

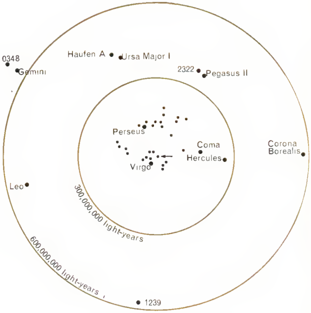
As exciting as the discovery of intergalactic material may be, its existence raises a difficult problem for the astronomer who wants to measure the distance of galaxies. We have seen that the distance of a galaxy is obtained by measuring the galaxy's brightness, and here is where we meet the problem. The more intergalactic material there is, the more light is absorbed on its way from the galaxy to an observatory on Earth. This means that all galaxies may well appear dimmer than they should. If we knew exactly how much intergalactic material there is—and how it is concentrated in space—we could work out how much light is being absorbed and then make allowances for it when we calculate distances. But unfortunately we do not yet know how much intergalactic material there is, or how it is distributed in space. Add this problem to the others we have mentioned and you will understand why astronomers are so cautious when they speak of distances for all but the nearest galaxies. And even the distances of the nearest galaxies have to be treated with some reserve.

In time, radio astronomers may be able to help solve the distance problem. We know that interstellar dust does not affect radio waves as much as it does light, and it may be that the same thing is true of intergalactic material, which probably contains some dust. If so, radio telescopes can help considerably. As an example of their power to penetrate dust, we have only to look at what they have helped us to discover about our own Galaxy. Because of the presence of dust in the Galaxy, optical telescopes are unable to photograph the central parts of the nucleus or the outlying areas of the Galaxy. But with radio telescopes the dust is of little consequence, and we can observe these regions. Radio astronomy has made it clear that we live in an Sb-type spiral galaxy, and that the Sun and its planets lie in one of the galaxy's spiral arms.

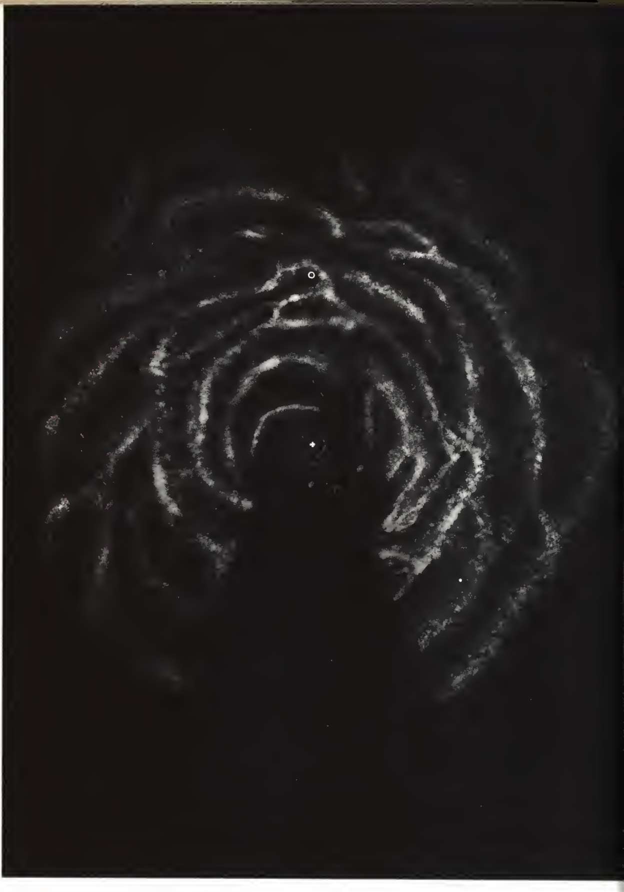
Not all the intergalactic material is likely to be dust; part of it is probably hydrogen gas like that contained within our own Galaxy. Although this gas is mostly invisible



The plan above gives at least a rough idea of how galaxies are spaced within the Local Group. (Our Galaxy appears at the center.) The plan below is drawn to a much smaller scale. On it our entire group becomes no more than one small dot right in the middle. Small dots indicate clusters of fewer than fifty galaxies. Large dots indicate clusters of more than fifty galaxies.



Opposite is a remote cluster of galaxies in Hercules. Round or spiky dots are stars of our Galaxy. Remote galaxies exhibit distinctive shapes.



With radio telescopes Dutch and Australian astronomers have detected and mapped the neutral hydrogen in our Galaxy and produced this picture. A cross marks the Galaxy's center and a ringed dot shows the Sun's position. In time radio telescopes may help us to map intergalactic space.

in optical telescopes, it can be detected by radio telescopes since it radiates radio waves of a length of 21 centimeters. If intergalactic hydrogen radiates at a similar wave length the radio telescope should once more prove to be the most important way of studying it, finding out how much of it there is, and how much radiation it absorbs.

In the past few years radio telescopes have proved their importance in the study of distant galaxies. Powerful radio sources lying far outside our own Galaxy have been detected and radio astronomers have asked themselves what these sources are. Are they galaxies, and if so, what kinds of galaxies? Some of the sources have proved to be objects that can be photographed with the 200-inch Palomar telescope, but others are too dim to be photographed at all. Those that have been photographed seem to be galaxies, and in one case a photograph shows what looks very much like two galaxies in collision! But one thing seems clear. Galaxies that are powerful emitters of radio waves are not necessarily bright galaxies. Possibly the opposite is true—that bright galaxies do not emit strong radio radiation. However, this does not mean that *no* radio radiation is received from near and bright galaxies, for radio waves are received from the Andromeda Galaxy and the Magellanic Clouds.

Whatever their actual distances, we know that the most distant galaxies are thousands of millions of light-years away. But what do we know about their speed and direction of motion? Are they all moving in the same direction and at about the same speeds? If we can answer these questions we will come a little closer to being able to draw up a plan of the universe. Right away we can rule out the possibility of detecting the motion of galaxies *across* our line of vision. Take the Andromeda Galaxy, for instance. It is only forty years since astronomers discovered that it lies beyond our own Galaxy. Suppose that the Andromeda were moving across our line of vision at a speed of 500 miles per second. In 40 years it would have traveled a distance of only about one tenth of a light-year. Considering that it lies at a distance of two million light-years from us, this "small" distance would be impossible to detect.

Although we cannot observe even a very fast motion across our line of vision, we can detect much smaller velocities toward or away from us. This we can do by making use of the Doppler shift of spectral lines. And when we apply this means of measuring we come up with some startling results. First of all, every single galaxy—except some of those in the Local Group—shows a red shift of its spectral lines, which means that almost all of the galaxies and clusters of galaxies around us are moving farther and farther out into space. In addition, the American astronomers Edwin Hubble and Milton Humason discovered that this outward speed, or *velocity of recession* as it is called, increases the farther away a galaxy lies. For example, one of the clusters of galaxies in the constellation

Galaxies that are powerful emitters of radio waves are not necessarily bright ones. Here is NGC 4038–9, a strong source of radio noise but not particularly outstanding for its visible radiation.

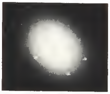
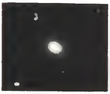
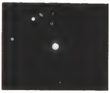
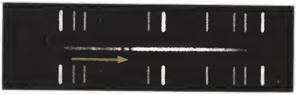
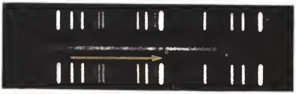
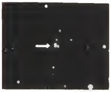
Virgo, about 40 million light-years away, is moving from us at 750 miles per second. A cluster in the constellation Ursa Major, which is nearly 500 million light-years distant, is moving away at a rate of 9300 miles per second. Yet another cluster of galaxies in Corona Borealis, nearly 700 million light-years from us, has a recession velocity of 13,400 miles per second.

These velocities of recession are impressive, but when we look at the figures for still more remote galaxies we find they are quite staggering. One very distant cluster, 3c–295 in Boötes (*different from the Boötes cluster shown opposite*) is 3500 million light-years distant, and is speeding away from us at 70,000 miles every second. What is more, there is no reason to doubt that still more distant galaxies, such as those that can be observed only with a powerful radio telescope, have even greater recession velocities. From all this evidence scientists have worked out the relation between how far away from us a galaxy is and how fast it is moving. It seems likely that for every increase of five million light-years in distance there is an increase of about 100 miles per second in speed. For instance, if one galaxy is moving away from us at 1400 miles per second, then another one that is five million light-years farther off will be moving away at about 1500 miles per second.

These facts bring us to what may seem a very strange conclusion—namely that there is a limit to how much of the universe we shall ever be able to observe! This is not because telescopes can never be made powerful enough to see farther or cameras sensitive enough to photograph dimmer objects. Even if we could go on increasing the power of telescopes and the quality of photographs forever, we should still come up against the same problem, because it arises from the very way the universe seems to be made. If we think of galaxies farther and farther away in space, we can see why this must be so. For every increase of about five million light-years in distance, the velocity of recession of the galaxies increases by about 100 miles per second. Let us see what happens if we begin with the galaxies in the Boötes 3c–295 cluster and then work outward. These galaxies, 3500 million light-years away, are traveling away from us at a speed of 70,000 miles per second. So if we imagine galaxies five million light-years farther off, they must have a speed of 70,100 miles per second. Continuing in this way, galaxies 100 million light-years farther away than the 3c–295 cluster are traveling at 72,000 miles per second; those 1000 million light-years farther away are travelling at 90,000 miles per second, and those lying more than 5815 million light-years farther away are traveling at more than 186,300 miles per second—which is the speed of light! So it is possible that galaxies lying 5815 million light-years farther off than the 3c–295 cluster, or *about* 9315 million light-years away from us, will forever remain invisible, simply because the light and radio waves they generate can never reach us. But astronomers are continually turning up new facts that will probably make it necessary to revise these figures, as these figures themselves have been revised from earlier values.

All our observation and reasoning, then, leads us to believe that we are living in a universe of which we can observe only a part. We are also finding that it is an expanding universe in which all the galaxies are rushing away from us—those farther off moving away at greater speeds than those nearer at hand. But why should every galaxy be moving away from *us*, or at least away from our Local Group? Is there something very special about our particular galaxy, or about our Local Group?

One way to get at the answer is to think of what happens when a bomb explodes. There is a flash of light, a big bang, and the casing of the bomb is broken into thousands of tiny fragments that are all sent flying outward in every direction. After a very short time the fastest moving fragments will be farther away from the center of the explosion than the more slowly moving fragments. If we had been able to stand at the center of the explosion and observe the flying fragments with a very sensitive spectrograph we

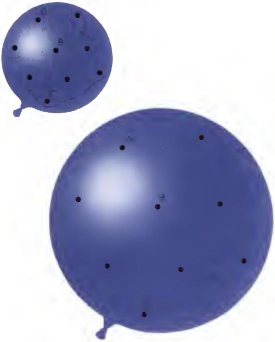
cluster nebula in	distances in light-years	red shifts.
 Virgo	40,000,000	 750 miles per second
 Ursa Major	500,000,000	 9300 miles per second
 Corona Borealis	700,000,000	 13,400 miles per second
 Bootes	1300,000,000	 24,400 miles per second
 Hydra	2000,000,000	 38,000 miles per second

In the left-hand column of pictures above are several clusters of galaxies lying at different distances from us. Oblongs at the right show how far their spectrum lines are shifted toward the red end of the spectrum. The greater this shift, the greater the speed at which they are moving away from us. Distant galaxies, we see, recede faster than near ones. The figures above may change from time to time as new discoveries are made, but this principle stands firm.

should have found that they all showed a red shift, those farthest away showing the greatest shifts simply because they had the greatest speeds.

From this example we might at first think that the universe exploded at some distant time in the past and that our Galaxy, or our Local Group, was at the very center of the "explosion." But if this were so, why does our Galaxy still exist? What prevented it from being blown to bits by the explosion? We can find an answer if we think about an exploding bomb from a different angle. This time we have to imagine that we were not at the center of the explosion but that we were on a piece of the bomb's casing, so that when the bomb exploded we traveled outward on one of the thousands of fragments. If all the other fragments, as well as our own, were still moving away from the center of the explosion, what would we see?

The first thing we would notice is not that we are moving away from the explosion but that every other fragment seems to be moving away from *us*. Next, if we observed the speeds of the other fragments we would find that those farthest away from us would have the greatest speeds. For instance, imagine that our own fragment is moving outward at four miles a second, that the fastest fragments are moving out at seven miles a second, and that the slowest ones are moving out at one mile a second. Looking ahead of us we would see the most distant fragments moving away from our own fragment at three miles a second (seven miles a second minus our own speed of four miles a second). Those not quite so far off would seem to be moving away more slowly (their own speed of, say, six miles a second minus our speed of four miles a second). If we next looked behind us, the most distant fragments would be those moving most slowly away from the explosion. They would be moving away from us at three miles a second (our speed of four miles a second minus theirs of one mile a second). Those not quite so far off would again seem to be moving rather more slowly (our speed of four miles a second minus their own speed of, say, two



As a balloon expands, marks on its surface move farther apart. Marks already widely spaced, like A and C, show a bigger increase in distance than closer marks (A and B). Clusters of galaxies seem to move apart in a similar way.

Lemaître (left) and Gamow (right) say the expansion of the universe probably began with some gigantic explosion.

miles a second). The fact is that no matter what fragment we happened to be on, all the other fragments would appear to be rushing away from us.

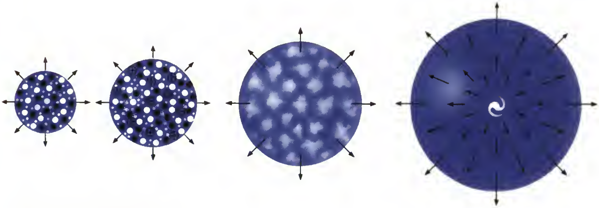
Our exploding bomb, whether we place ourselves at the center of the explosion or on one of the fragments flying away from the center, accounts nicely for what we would observe and for what in fact we do observe. All of the galaxies, except those making up our Local Group, seem to be rushing away from us as if some cosmic explosion actually did take place thousands of millions of years ago. But just how far can we carry this idea? Could the matter now making up the planets, stars, and galaxies, and occupying intergalactic space, ever have been gathered as a superbody of some kind that did explode?

How Did the Universe Begin?

If we could answer this question we would solve a puzzle that has excited men's minds for a long time. And as we have theories that attempt to account for the formation of planets, stars, and galaxies, we have others that attempt to account for the birth of the universe as a whole. One group of theories would have us believe that the universe began with a cosmic explosion, while another group says that the universe is in a state of "continuous creation." Let us look first at the "big-bang" theory, as it is sometimes called.

The noted Belgian astronomer Georges Lemaître has suggested that 20,000 million years or more ago the universe began as a kind of "superatom." This "superatom," or *primeval atom,* as it is usually called, is supposed to have contained an incredible amount of material packed tightly together. It is also supposed to have been highly radioactive. Because of the intense amount of radioactivity, the primeval atom disintegrated, or exploded, within moments after it had been formed. From this explosion the expansion of the universe began. In due course the material began to condense and form clusters of galaxies.

According to Lemaître, the force of the explosion would not have been strong enough to keep the universe expanding. Einstein's explanation of the behavior of light and other radiation in the universe next led Lemaître to the conclusion that there must be another force that keeps the galaxies moving apart. This force is usually called *cosmical repulsion* because it causes all of the galaxies to be repelled from each other, and Lemaître holds that it becomes important only over really large distances. Over



Here we see Lemaître's idea greatly simplified. The first circle shows the *primeval atom* just after the explosion. Soon (next circle) it begins to cool. Its particles combine to form the nuclei of atoms.

After 30 million years of expansion and cooling, clouds of gas and dust form. These are raw materials for galaxies.

In time the initial explosion loses its force. Then *cosmical repulsion* takes over, and this keeps galaxies moving apart.

small distances it is unnoticeable because its effects are completely swamped by the effect of gravity, which tends to pull things toward each other. According to Lemaître, then, it was the force of the original explosion that first set the condensing galaxies moving apart. When, in course of time, that force had weakened, the galaxies had condensed so much that most of the material of the entire universe was concentrated into them. At that stage cosmical repulsion took over and kept the galaxies moving apart in the way we now observe.

George Gamow, an American astrophysicist, has also put forward a "big-bang" theory to account for the beginning of the universe. Gamow's ideas are in some ways simpler than those of Lemaître. He also believes that the expansion of the universe began at the moment the primeval atom exploded. Gamow has been particularly interested in the formation of the chemical elements we find in the universe, and he has worked out details of the temperature which the primeval atom would have had to reach in order to form them. He believes that the temperature of the primeval atom was so high, and the force of the explosion so great, that these alone would have been enough to make a continuously expanding universe possible. So in Gamow's theory there is no need to introduce Lemaître's idea of cosmical repulsion.

The second explanation of how the universe could have begun does not depend on an explosion. The British astronomers Herman Bondi, Thomas Gold, and Fred Hoyle have come to the conclusion that in any really large part of space there is always the same amount of material. But if the universe is expanding, as the outward movement of the galaxies indicates, the quantity of material in every part of space should be steadily becoming less and less. To meet this difficulty, Bondi, Gold, and Hoyle have suggested that new material is constantly being formed in space. This material, they say, takes the form of hydrogen atoms. Although the amount of newly formed material in each cubic mile of space is too small to be detected, the universe is so immense that the total amount of new material is quite enough to condense into new galaxies. And these new galaxies, as they come into being, keep the total amount of material in any large region of space always the same.

So in this theory the *total* amount of material in any large part of the universe never varies. What is taken away by a receding galaxy is eventually replaced by a new

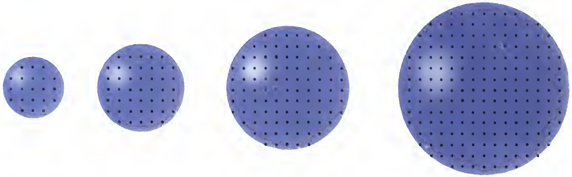
These men (Bondi left, Gold center, and Hoyle right) say the universe had no beginning and will have no end.

galaxy condensed out of new material. If this is really so, in any large part of the universe things must always look very much the same. If we could visit our own area of the universe 100,000 million years from now we should find the same amount of material there. Our Galaxy would have moved off with others of the Local Group, but they would have been replaced by new ones. In other words, in spite of expansion, the universe seems to be in a fairly steady state, and the Bondi-Gold-Hoyle idea has come to be called the "steady-state" theory.

According to the steady-state theory, the formation of hydrogen atoms has *always* been happening. This means that galaxies have *always* been condensing, so however far back we go in time we still find a universe with galaxies expanding into space. If this is true, the whole universe, strange though it may seem, never really had a beginning at all. We can speak of the age of this galaxy or of that one, but we cannot speak about the age of the entire universe. It has existed for all time and will continue to exist forever!

Some astronomers do not like the idea of a steady-state universe in which new atoms of hydrogen are constantly being formed. They want to know exactly *how* the hydrogen atoms come into being. On the other hand the ideas of Lemaître and Gamow raise an equally awkward question. Both of these theories assume that the universe began from a primeval atom of a peculiar kind. But how did this "superatom" come into being?

Perhaps we shall never learn the answers to these questions. On the other hand, today we can answer questions that would have been impossible for early Greek astronomers to have considered, one reason being that they did not have the tools and mathematical concepts we have today. The details of how galaxies come into being, how they conduct their lives, and how the whole universe began, remain to be settled by astronomers of some future age. Meanwhile we must be content to study the possible explanations now available to us, recognizing that at some future time new and more satisfying theories will doubtless emerge.



They say that although the galaxies are always moving farther away from each other, new matter is always being created out of which others will form. So in any large area, over a long period, the galaxies are equally spaced.

6 The Way Ahead in Space

From the beginning of this book we have seen that men have been asking questions about the universe for many centuries. The answers they found at different stages of history depended largely on how far science, technology, and mathematics had developed at the time. What was the "truth" for men of one age often had to be discarded and replaced with new "truths" by men of a later age. The search for new scientific truths is endless and the same kind of questioning is still going on today. Although scientists of our own age have found very convincing answers to such questions as what makes the stars shine? and what sort of life histories do stars have? they face even broader questions. Quite a few of these broader questions we have been able to ask only in fairly recent times. The ancient Greek astronomer Hipparchus, for instance, could not have asked why the universe is expanding, because astronomers of his time had neither the knowledge of the existence of galaxies, nor the means of measuring their motions.

When we ask how galaxies are formed and how they age, or how the universe itself began, we are faced with the fact that different astrophysicists have quite different answers and that they cannot all be right.

What are our prospects of learning more about the universe so that we can give more confident answers to the many questions that continue to baffle us? Within the next few years we can expect to collect better observations of the Sun, Moon, stars, and planets than ever before by using telescopes and other instruments mounted in artificial satellites. And manned space travel promises firsthand reports of conditions on the Moon, Mars, and Venus. Before this century ends we may make the first attempts to communicate with life on planets that orbit around stars other than the Sun. But before we make too many prophecies we should first look at some of the things we are already fairly sure about, see just what problems they pose, and then ask how we can expect to solve these problems.

Here men adjust panels of solar batteries of Mariner II before its launching from Cape Canaveral in the summer of 1962. On the opposite page is an artist's impression of the spacecraft speeding on its way toward Venus to make close-up observations. Flights of this kind add much to our knowledge of space.

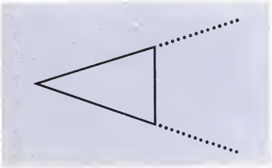
The Shape of Space

In the last chapter we found that there seems to be a limit to the amount of the universe that we shall ever be able to see. This is because galaxies more than about 9500 million light-years away from us are rushing outward into deep space at the speed of light so that none of their radiation can ever reach the Earth. We can think of the whole *observable* universe, then, as a globe with a diameter of something under 20,000 million light-years. If we ask whether other galaxies lie outside this observable universe we can say only that we do not know for certain, and we may never know. But we may equally well say that it does seem very likely that there are others. We can ask, then, how far *do* the galaxies extend into space? Do they go on "forever" or is there an end somewhere?

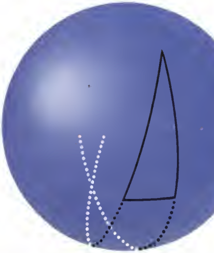
The answer is not at all easy to work out because astronomers have very good reasons to believe that space folds over on itself in a peculiar kind of way that can be described only with the help of very special mathematics. Although we cannot draw a picture of this kind of space, we can get at least some idea of it if we take an example of how we sometimes have to readjust our ideas about geometry on Earth. Here is a very simple one. Suppose we want to travel from our own house to another house just along the street. To get there in the most direct way we walk in a straight line, because experience has taught us that a straight line is the shortest distance between two points. But now suppose that we want to travel half way around the world. On the two-dimensional surface of a Mercator map we can plot our journey as a straight line and record the progress of our aircraft along this line. But in reality the jet clipper we are flying in traces a curved path that follows the curvature of the Earth's surface. While there is no harm in thinking about the world as flat if we are considering only a very small part of it, when we consider a large part of it we must abandon our concept of straight lines and think instead of curved lines.

So it is with the universe or cosmos. When we are dealing with the Solar System or with our own Galaxy we can use ordinary mathematics to measure distances in straight lines and orbits as curves, using the simple kind of geometry we first learn in school. We can also think of the distances to other galaxies in this way until we begin to ask where they are expanding to. Then we must realize that our ordinary ideas are not good enough. This is because most of us base our ideas of space on what we observe of comparatively nearby

If we draw a triangle on a flat sheet of paper we are dealing with geometry of a familiar kind. We know, for instance, that when we extend two of its sides farther and farther from the angle they enclose they will not meet.



If we work on the surface of a sphere (the shape of the Earth) our geometry changes. Now when we extend two sides of a triangle they first get farther apart but eventually they converge and meet on the far side of the sphere.



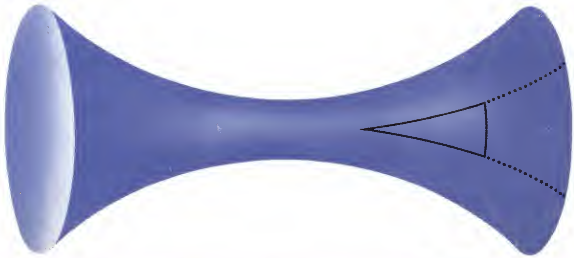
objects, such as the Sun, the planets, and the nearer stars. When we begin to think about the whole universe, however, our local ideas of space and geometry simply cannot take us far enough.

In traveling over the whole Earth we have to think about curved routes simply because the Earth is a globe. According to the modern idea of the universe, we also have to think of space as being curved. Although all the galaxies we can observe appear to be moving away from us in straight lines, they are actually moving in curved paths, as do all objects in space. This curving is so slight that we cannot detect it by experiments on Earth, or even by observations in the "local" areas of space. It is only over great distances in the universe, distances of hundreds of millions of light-years or more, that the curving really shows up.

If space is curved in the particular way astronomers believe, and if everything in space moves in the kind of curved paths they visualize, it follows that things can just go on moving and moving forever. Because a galaxy's path is curved in this way, it will never come to the "edge" of space. To put it in another way, we can think of the curved paths traced by the most distant galaxies we can ever observe as forming the "edge" of "our" space; but "our" space is not necessarily all the space there is. Some astronomers think that although space is certainly vast there is only a fixed amount of it, and they call it a *finite universe*, which means a universe that has limits. But they also believe that all the galaxies in it can go on expanding away from each other forever. This can happen because space is not simply shaped like a globe but is "curved" in a different and more complicated way. Because we cannot draw this kind of curvature, we must use the language of mathematics to think about it.

If all of this seems strange we must remember that the universe itself is strange in many ways when judged by our normal Earth-bound standards. Its distances are unimaginably vast and the objects in it are fantastically immense, so we should not be too surprised to find that we cannot think of the greatest distances in space in the same kind of way as we think of distances on Earth. When the ancients attempted to come to grips with this problem they, too, found difficulties when they tried to explain the nature of space by using Earth's standards, One explanation described the universe as a great hollow sphere with the Earth at the center. From his position on the Earth man

Here yet another shape calls for yet another change of geometry. All this helps us to see why astronomers who think that space is curved in some peculiar way cannot draw it or describe it with the help of simple geometry.



sees the sphere's inside surface on which the stars march in endless procession. But then comes the embarrassing question of what lies outside the sphere. The answer can only be "nothing." And here is where the trouble begins when we try to visualize a physical model of space. How do we explain "nothing" when confronted with this problem? Melissus, a Greek philosopher who lived about 440 B.C., said: "Nor is there anything empty, for the empty is nothing and that which is nothing cannot be."

If space really is folded over in a kind of curve that forms the "edge" of the universe, it means that in one sense there is no end to space. You simply cannot come to the "edge" of space, however you move or think of moving, any more than a ship can arrive at the "edge" of the world, since there is an ever-changing horizon-edge. Although our Earth has a strictly limited size, for a ship there is always more world for it to travel over; and for a galaxy there is always more space for it to expand into. But here we must be cautious. Astronomers cannot be certain that this idea about the special curvature of space is correct. It may be no more correct than the idea of epicycles that Ptolemy and his successors used to explain the apparent motions of the planets. Yet it is certainly the best explanation we have at the present time, and we must make as much use of it as we can in describing the universe.

Accepting the idea of an expanding universe with definable limitations—and also remembering that we can never observe galaxies more than about 9500 million light-years away—we must remember that our knowledge of the universe depends on our observations of only one part of it. So here we have one of the big problems posed by our present knowledge of the universe: Is the part of the universe that we can never observe just like the part we can see? How can we ever know? The answer is that we should not let it worry us too much because astronomers have always had to depend on whatever limited methods were available to them, and then draw the best conclusions they could.

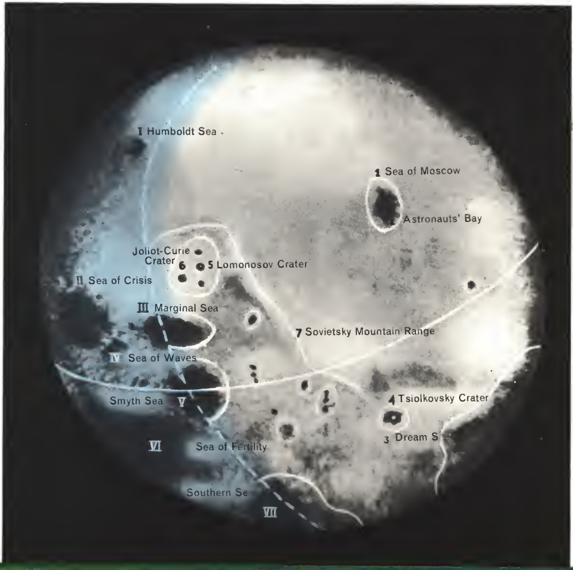
Here is an example of how this system of thinking works. About 10 years ago the American astronomer Ralph Baldwin

On the Moon's visible side (right) are vast lava "seas." From a theory of how they were formed one astronomer argued that the far side of the Moon would not have such big seas. He made this prophecy before the far side of the Moon was observed. Later a Lunik III photograph (far right) proved him right. Today astronomers may well have right ideas about areas of space not yet observed.

worked out a theory explaining how the Moon's "seas"—actually vast solidified plains of lava—were formed. He said that about 4500 million years ago a gigantic piece of rock about 200 miles in diameter crashed into the Moon. Traveling at a speed of $1\frac{1}{2}$ miles a second, it struck a region called Mare Imbrium. The amount of energy generated by this impact was so great that a flood of lava poured out of the Moon's interior and covered vast areas of its surface. About one half of the side of the Moon facing us is occupied by these dried-lava seas today.

Although our telescopes reveal lunar seas on the visible face of the Moon, astronomers wondered if they also existed on the far side of the Moon that is forever hidden from our view. Some astronomers felt that the far side must have features very much like those on the near side. But the American astronomer I. M. Levitt did not agree. He felt that the hidden side "is wholly unlike ours in that it is rougher and lacks great sea areas." He felt that this must be so if Baldwin's theory were correct. In October 1959, when Russia's Lunik III televised pictures of the far side of the Moon, Levitt's thinking was shown to be correct. The point of all this is that with only a few facts at hand we can sometimes build up a reliable picture of something that we have no direct, clear-cut means of proving.

It is only by relying on the best methods available to them at the time that astronomers have built up our modern picture of the universe. This is also the way in which our ideas of the atom have been worked out, and it is the method that all scientists use to discover new knowledge. They do their best with the facts and theories that they have.



Life on Other Worlds?

This is just the kind of method we must use when we try to answer the question: How many planetary systems are there in the universe? So far we have not been able to observe any whatever except our own Solar System. Does this mean that our planetary system is unique, or that such systems are very rare? Since we cannot yet actually observe any others, we can only argue from the one planetary system we already know. Let us see where such an argument leads us.

We know that the planets of the Solar System do not give out light of their own making, but only reflect the light of the Sun. We also know that the Sun is a star and that all the planets of its system are orbiting around it. From this we can conclude straight away that any other planetary systems there may be must be attached to a star. The next question is, what kind of star? Here we cannot be quite so certain, but we are fairly sure that a red giant would probably be too big. Since the outer layers of gases of these stars extend so many millions of miles into space, they would envelop all or most of the planets orbiting about them. O- and B-type stars are so intensely hot that any planets orbiting about them would be vaporized. So it would seem most likely that any other planetary systems that exist will belong to other types of star—G-type stars like the Sun, or F-type stars. But will all the stars of these other types have planets orbiting about them? To try and find an answer to this we must begin by considering how our own planetary system came into being.

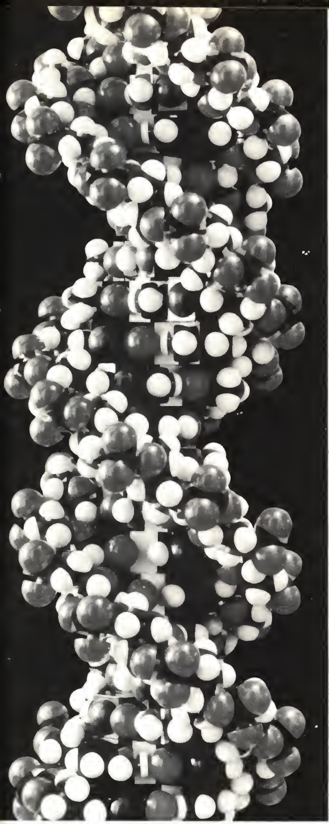
We found in an earlier chapter that there were a number of different ways in which this could have happened. Several theories suggest that the planets were formed by some accident. Some say it was as the result of a collision or near-collision with another star. Others say that the Sun was once a member of a binary system and that the planets were formed when the Sun's partner-star either became a nova or collided with a third star. Whichever of these theories we accept, the point is that all of them assume that the Sun's planets were formed as a result of some kind of catastrophe. If any of these theories is correct, then the formation of our planetary system was a chance happening, and the number of other planetary systems that exist will depend on how likely or unlikely such a chance was.

Let us imagine that the chance of a similar catastrophe happening to other stars is extremely slender, say a million to one against. Since there are more than 10,000 million G-and F-type stars in our own Galaxy, this would mean that about 10,000 of them might have met with a similar catastrophe, and could be expected to have planetary systems of their own. And our Galaxy is only one of millions. So if any of these theories is correct, there is a strong likelihood that a very great number of other planetary systems exist throughout the universe.

But we have also seen that there is quite a different theory to account for the formation of the Solar System—the theory that the planets condensed out of dust and gas "left over" when the Sun itself was formed. If this theory is correct, then the formation of a planetary system does not depend on some catastrophic event; and it would then seem likely that planets form around most stars as they condense. In that case there ought to be thousands of millions of planetary systems in our own Galaxy alone, and countless millions in the galaxies of the whole universe.

Let us suppose for a moment that there are thousands of millions of other planetary systems. We can then ask ourselves another question: Is there life on any of these planets, and if so, what is it like? The first thing to make clear is that we cannot be certain what the correct answer is. But this does not prevent us from putting certain facts together and finding the most likely answer that our present knowledge can give us.

As a first step we must ask what we mean by "life". All of us probably have some idea of what we mean, but it is very difficult to put into words. Even biologists find it difficult to say exactly what makes a living thing different from a nonliving thing. So for our purposes it is best to simplify our original



Here is a model of a carbon-backbone molecule of DNA. Such molecules are the basis of life but can exist only at the right temperatures. Stars are too hot for them, some of the Sun's planets too cold. Yet there may be countless planets in the universe where they—and life—do exist.

question and ask: Do plants, animals, or creatures like human beings exist on other planets?

Here the study of astrophysics gives us some important facts to work on. The first one is that the 92 natural elements that we know on Earth are the same 92 elements that are found throughout the universe. It is true that in different stars we find these elements in different amounts, but the important point is that there are not any others. So if plants or animals have evolved on other planets elsewhere in the universe they must have been built up out of just the same elements that we have on Earth.

When we next examine the make-up of the great variety of living things on Earth we find that only one element out of the 92 is used as the basic atom for all living material, and that is carbon. Carbon has the ability to form giant molecules because its atoms can link together in immensely long chains. With a carbon chain as a "backbone," other atoms can join on and very complicated molecules can be built up. These complicated "carbon-backbone" molecules are the atomic building bricks from which all living things are made. It seems, then, that to have living things we must have large, complicated molecules. But must they be made out of carbon? Will no other elements do?

The answer seems to be no. The only other atom that can form long chains is silicon. However, silicon chains are not so long as those of carbon, and if we use artificial methods to make them very long, they immediately break up. So it looks as though we must have carbon as our basic atom. This means we can say at once that there are many places where plants and animals cannot exist. Wherever it is too hot carbon molecules will be broken up; wherever it is too cold new carbon-backbone molecules cannot build up from other carbon-backbone molecules, and all the chemical processes that go on in living things come to a stop. So we can definitely say that no living creatures of any kind can live on stars. The temperature of even the coolest stars of the main sequence is about 2000°c. The sensitivity of

carbon molecules to high temperature would also rule out life of any kind on Mercury, whose side facing the Sun reaches about 370°C., or 700°F., hot enough to melt lead, and whose dark side is near absolute zero. But what of the other planets of the Solar System?

Pluto would seem to be too cold and so would Neptune and Uranus, for observations show their temperatures to be about −160° to −170°C. Saturn and Jupiter do not seem to be much better. They have dense atmospheres containing methane and ammonia, and their temperatures are no more than −135°C. Really cold temperatures like these mean that plants and animals would have no energy to carry out the chemical and other processes necessary for life. So unless the temperatures below the dense atmospheres are much warmer than astronomers think (which seems unlikely), and unless there are regions where the poisonous methane and ammonia are less in amount, we must count Jupiter and Saturn as uninhabitable by any kind of life.

We have eliminated Mercury, Pluto, Uranus, Neptune, Jupiter, and Saturn; we can also eliminate the asteroids because they are too small to have atmospheres of any kind. This leaves us with only Mars and Venus. On Mars there are large bluish-green patches that change in size with the change in the Martian seasons. Near the poles, water in the form of snow or frost is to be found, but other parts of the planet seem to be without water. Near the equator temperatures are often above freezing and reach 70°F. or more in summer. Astrophysicists have also found that the comparatively "thin" atmosphere of Mars is not poisonous, although it would not be of use to explorers from Earth because of its thinness and the very small amounts of oxygen and water vapor. Most astronomers think that the bluish-green patches are vegetation of some sort, but exactly what has yet to be determined.

The American astronomer Percival Lowell romantically regarded Mars as a planet that once supported intelligent beings, and which we see today in its last stages of life. He said that over the years the planet's water supply had gradually disappeared. "The drying up of the planet is certain to proceed until its surface can support no life at all," he wrote in his book *Mars as the Abode of Life*. "Slowly but surely time will snuff it out. When the last ember is thus extinguished, the planet will roll a dead world through space, its evolutionary career forever ended." Astronomers today do not accept this view.

Even in the Solar System our Earth may not be the sole abode of life. On the left is a drawing of Mars made by Dr. de Vaucouleurs of Harvard College Observatory. It may well be that the greenish patches represent vegetation. Opposite, greatly magnified, is a fragment of a meteorite. The spot near the arrow is very much like certain algae found on Earth. Perhaps in other planetary systems there are far higher forms of life, including intelligent beings.

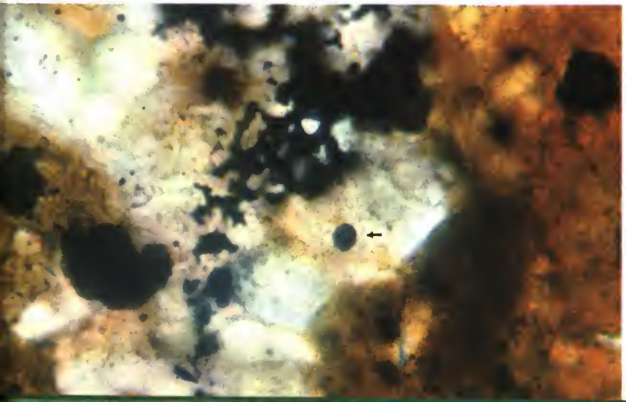
Although simple life most likely exists on the planet, no one would dare say at what stage of evolution it is.

On Venus all we can observe is a thick, cloudy atmosphere and, unlike Mars, the nature of the planet's surface and its rate of rotation are still a mystery. Astronomers do not agree about the composition of the atmosphere or the thick clouds floating in it, although large amounts of carbon dioxide and some water vapor seem to be present. What does seem to be clear is that the surface of the planet, whatever it may be like, is probably very warm. Indeed, Mariner II gives a temperature of 425°C. Some astronomers think that this is too hot for there to be any life. Others, who believe that there may be vast oceans on Venus, suggest that there might well be at least some kind of bacteria that could perhaps exist in the water.

What this investigation boils down to, then, is that out of the nine planets orbiting the Sun, three at most—Mars, the Earth, and possibly Venus—seem to be places suitable for supporting life. If our own planetary system is a typical one, this means that at the most something like one in three planets of every planetary system might be suitable for living things. So if we are correct in thinking that there are thousands of millions of planetary systems in the universe, then it is quite likely that there are many millions of planets on which there are living creatures of some kind or another. We saw earlier that even a low estimate suggests that our own Galaxy alone contains about 10,000 planetary systems. If, on the average, they include nine planets, as the Solar System does, then our Galaxy may hold something like 30,000 planets on which there could be satisfactory conditions for life!

While it is highly likely that there is an abundance of life of some sort elsewhere in the universe, what about the existence of intelligent beings—creatures with an intelligence similar to our own? Again, we cannot be certain. We can only argue from what we know of the Solar System. Here, one of the three planets suitable for supporting life has intelligent beings on it. Can we, as a first guess, assume that in any other systems one out of every three planets with life on it is likely to be the home of intelligent creatures?

This is probably stretching things too far. Intelligent creatures have lived on Earth for only a very short part of the time during which conditions have been suitable for life. The Earth has existed for about 4500 million years, and tool-making men for only a million years or less. If life on other planets has



evolved along the same lines as on our own, then we must ask how many of the 30,000 planets with conditions suitable for life are at the same stage of evolution as the Earth. Here we are at a loss. Any figure we gave would have to be a guess.

About all we can say is that if planets are normally formed when stars condense, there are far more planetary systems in our Galaxy than we have supposed; and those supporting intelligent beings may number in the hundreds at least, if not in the thousands. And for the entire universe the figure may be in the millions. Man is certainly not alone in the universe. The trouble is, of course, that we have not yet been able to prove it; furthermore, we cannot say which particular stars have planets on which other intelligent beings may be living. Is there any way of finding out?

One radio astronomer has suggested that we might be able to communicate with such beings by radio. What we would have to do is send out a series of radio messages from a radio telescope, and then wait for an answer. First we would have to decide on the direction in which our message should be beamed. The best plan would be to beam it toward several stars similar in age, size, and temperature to the Sun. We would also need to choose a star that is reasonably close, for two reasons. First, we want our radio message to be received as strongly as possible, and the nearer the star and its planets are to us the more strongly will our signal be received. The second reason is that we want the time between sending our message and receiving an answer to be as short as possible. Even if we choose the very near star α Centauri it would take at least nine years before we have a reply. Traveling at the speed of light it would take our radio signal $4\frac{1}{2}$ years to cross the 27,000,000,000,000 miles to α Centauri, then another $4\frac{1}{2}$ years for a reply to reach us—plus the time it would take the Alpha Centaurians to decode our message and code a reply. If we were to choose a star that is too far away, the Earth astronomers sending out the message would not live long enough to receive the reply!

Since we know nothing about the kind of language intelligent beings of another planet might use, what sort of message could we send them? If they were intelligent enough to build a radio telescope capable of receiving our signals, they would surely have a system of mathematics. So at first our messages could take the form of a sequence of pulses of radio waves—say half a dozen spaced every half second. After a pause of perhaps half a minute the same sequence of pulses could be sent out again. This simple transmission could be continued for a day or so, but with the number of pulses in a sequence varied from time to time, first sixes, then tens, then sixes, then tens, then sixes, then twelves, and so on. A long series of equally spaced pulses, as regular as the tick of a clock, might conceivably be produced by some natural phenomenon. A rhythmical but varying sequence would suggest the work of some intelligent agency.

The result of all this would be that radio astronomers on another planet who picked up these sequences would realize that there were other intelligent beings as well as themselves in the universe. Once they knew of our existence, they would transmit similar and more complex messages back to us. Simple arithmetic followed by higher mathematics would become the first interstellar language enabling us to communicate with beings on another planet.

Of course this whole idea is based on a number of things that we are taking for granted. We are assuming that other intelligent beings will be scientifically minded, that they will be interested in astronomy, and that they are advanced enough in science and radio engineering to make radio telescopes. We are also assuming that they will be tuned to the wave lengths we use, and that when they pick up our messages they will think it worthwhile to reply. At the moment we have no radio telescope powerful enough, and with time enough, to do the job well. Although we will probably have one soon, the small scientific value of this project does not make it worthwhile spending much time or money on it just at present.

Observatories in Space

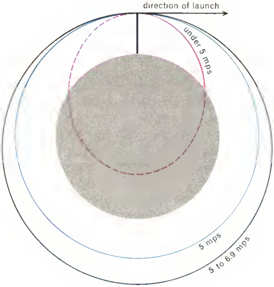
There are other equally exciting possibilities that seem to be just around the corner, especially possibilities of new and better observations. This is because astronomers are now at long last able to observe the heavens without the Earth's atmosphere getting in the way. For the first time in history astronomers are building observatories to be sent out into space. The idea of making them completely automatic and launching them as satellites is so that they can transmit their results direct back to Earth. Having telescopes outside the Earth's atmosphere enables us to study the entire range of electromagnetic radiation sent out by the Sun and other stars, instead of only a small fraction of it, as was formerly the case.

Astronomers have long wanted observatories in orbit, carrying two different kinds of telescope—an optical reflector and a radio telescope. They have designed an optical telescope that sends its results back to the Earth by radio, the radio signals being generated by a special kind of television camera attached to the eyepiece end of the telescope. The image that the camera produces is "stored" on the camera tube long enough to allow the satellite's television unit to scan the picture slowly and transmit it piece by piece back to Earth. The electromagnetic pulses that carry each piece of the picture are picked up on Earth by a special television receiver. This receiver has no screen but is designed to put the results directly onto a photographic plate.

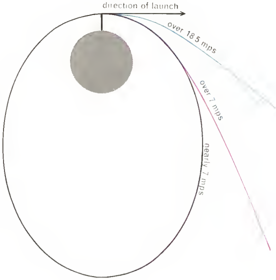
The telescope records not only straightforward pictures of the heavens, but can also be used to make observations through a spectroscope. The spectra obtained are sent

If intelligent beings exist elsewhere can we establish contact? We could at least beam powerful radio signals to let them know *we* exist.

At the moment our largest radio telescopes, such as the Australian one below, are too busy on other work, but this will not always be the case.



Space observatories collect information from rays that cannot reach the Earth's surface. If an observatory is launched at under five miles a second it falls back to Earth. At five miles a second it orbits in a circle.



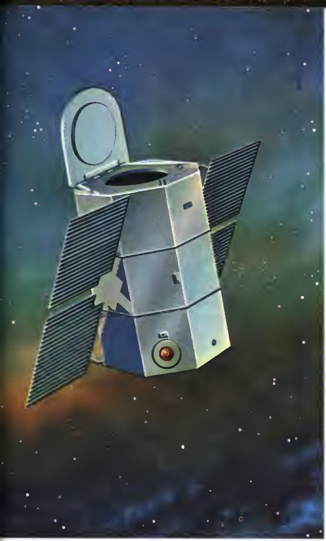
At speeds between five and seven miles a second, it will travel in an ellipse about the Earth (the higher the speed, the narrower the ellipse). At still higher speeds it will move in an orbit about the Sun, or about our Galaxy.

back to Earth in a way similar to the ordinary telescopic pictures. The observatory (and equipment) is designed to be fully automatic, but astronomers on Earth can still alter its program if they wish to by remote radio controls. Once in orbit, the satellite can send us information for a very long time, because its electricity will be generated by solar batteries.

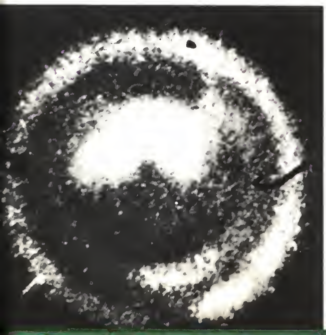
The radio telescope, also automatic, is capable of remote control by radio astronomers back on Earth. One of its features permits the operator to change the wave lengths at which the telescope works. This makes it possible to study different parts of the heavens at various radio wave lengths that are prevented from reaching Earth-bound radio telescopes by the Earth's atmosphere.

A second space astronomy project is concerned with putting an optical telescope in orbit around the Moon. In certain respects a 20-in lunar telescope can be as effective as the 200-inch Palomar instrument. Are the advantages of observing from outside the Earth's atmosphere really great enough to make these experiments worthwhile? The answer is a most emphatic yes. After all, our picture of the universe has been built up by studying only the light and other radiation that our atmosphere allows to come through. Now, at last, we have a chance to make use of all the "forbidden" wave lengths that for so long have been kept away from our Earth-bound telescopes.

One of the serious difficulties that has always faced astronomers is the fact that the Earth's atmosphere, with its restless currents of cool air, warm air, and dust never stays still. This means that in ordinary telescopes the images of stars and planets are never



Above is a one-ton American orbiting observatory intended to relay new astronomical information to Earth. Below is an X-ray photograph of the Sun taken from a rocket.



steady for more than a fraction of a second at a time. The movement is not very great, especially at large observatories built on mountains, but it is enough to limit the detail that an astronomer can photograph, because it takes time to expose a plate. This is particularly noticeable in photographs of the planets. However powerful the telescope and however good the camera we use, the photograph always seems to be fuzzy and never shows as much detail as an observer can see when he looks through the telescope. This is also true of photographs of the Moon. An observer with a small telescope can see almost as much as can be photographed with a much larger one.

With telescopes outside the Earth's atmosphere, all the difficulties due to dust and air movements are avoided. What is more, we can photograph the Sun's corona far more easily and farther out into space than the most effective coronagraph situated on the highest mountain ever can. This is because in space, where there is no atmosphere to scatter the Sun's light, we can reveal the corona in its full glory when we block out the image of the Sun's disk. In addition to all this, Earth-orbiting telescopes can study the Earth itself from outside and so provide new information about the upper atmosphere.

Optical telescopes orbiting the Moon can build up photographic maps and reveal details of its surface with a degree of accuracy never possible before. This means that stereo photographs can be made in a way similar to that used for aerial surveying on Earth. Radio telescopes can also make detailed maps by radar. To do this they must send out strong bursts of radio waves and measure how long the bursts take to reach various parts of the Moon's surface and to be reflected back again. This method, which has already been used to map meteors and meteor tracks from Earth, promises to be very accurate. Moon-orbiting observatories can also be used to study dozens of other aspects of the Moon's surface that have baffled us for many years.

Somewhat further in the future we can look forward to the time when men will land

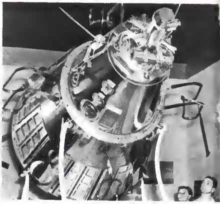
on the Moon and build an observatory there. This will be a great step forward for astronomy. If men can build a large reflecting telescope and large radio interferometer telescopes on the Moon, these instruments will be able to probe into space and examine distant galaxies whose radiation never reaches our Earth-based instruments because it is blocked by the atmosphere. Of course it will not be easy to build such instruments on the Moon. There is no air there and no protection from the Sun's rays nor from the intense cold of space. On the other hand, the pull of gravity on the Moon is only about one sixth as powerful as that at the surface of the Earth. This means that large telescopes will not be so heavy as on Earth and therefore need not be so rugged.

These, then, are just a few of the exciting ways by which we can hope to increase our knowledge of the heavens, learn more about the way stars and galaxies age, and come to firmer conclusions about how the universe began. But man's quest for new knowledge will not end there. Almost certainly the Moon will serve as a stepping stone from which man will explore the planets. We can therefore look forward some day to having satellite observatories orbiting every planet of the Solar System, and transmitting information back to Earth. And there is a good possibility of landing instruments on some of the planets. But what about man himself? Will he be content to land on the Moon, explore its surface, but go no farther?

Before the end of this century men will probably have landed on Venus and Mars. We can also expect that they will successfully return home to Earth and bring with them firsthand descriptions of those planets, samples of the materials they are made of

Here are some of the craft that were launched from the Earth during the first few years of the Space Age. Each marked a milestone in preliminary space exploration. Each was a stepping stone to new knowledge of the universe

Sputnik I
The first artificial Earth satellite went into orbit on October 4, 1957. It carried transmitters, pressure meters, and a radiation counter.



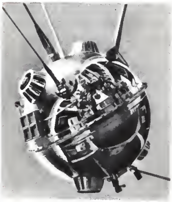
Sputnik III
Launched on May 15, 1958, and weighing over a ton, this satellite was equipped with instruments used in studying the Earth's outer atmosphere.

Lunik II
History was made when this strange spherical object was launched in September 1959. It became the first thing from Earth to reach the Moon.

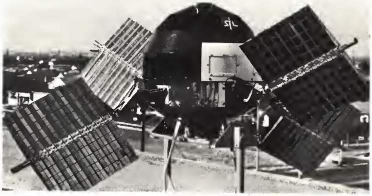
Sputnik II
This much larger satellite, launched in November 1957, carried a dog and instruments to check its bodily reactions to the new environment.

Explorer I
The first American satellite, launched on February 1, 1958, made measurements of cosmic radiation and meteorites. Discovered Van Allen Belts.

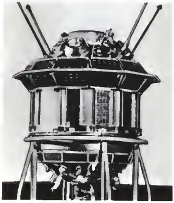
Vanguard I
This satellite, launched on St. Patrick's Day, 1958, had a solar-powered transmitter. Its aims included fixing the Earth's shape more precisely.



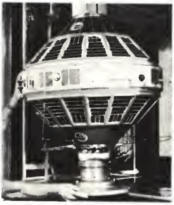
Lunik I
On January 2, 1959, Lunik I set out to make a close-up study of the Moon. It became not an Earth satellite but an artificial planet of the Sun.



Explorer VI
This satellite, launched in August 1959, was remarkable for its solar paddles and its instruments for research on radiation and magnetic fields.



Lunik III
Exactly two years after the launching of Sputnik I this craft began its successful photographic reconnaissance of the far side of the Moon.



Explorer VII
Nine days later (October 13, 1959) Explorer VII began orbiting the Earth, studying radiation, magnetic storms, and weather patterns.

Explorer XI
In April 1961, this satellite, equipped with a special telescope, began measuring the intensity and distribution of gamma-ray sources.

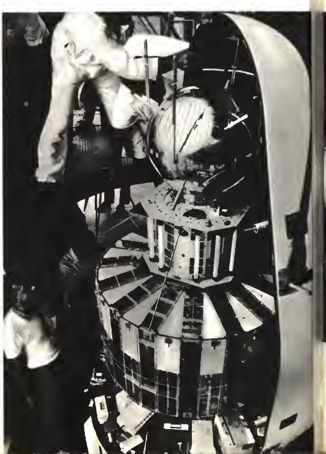
and any living things found on them, together with photographs of what they saw. Journeys across space take much time: a few days to the Moon, four months to Venus, seven and a half months to Mars. To Jupiter it would take five years and to Pluto about 45 years. But will astronauts ever be able to explore the planets of other stars and one day, perhaps, even visit other galaxies?

The answer, unfortunately, seems to be no. This is not because man cannot design a spacecraft good enough to undertake such journeys. It is simply because a space crew would not live long enough to travel the enormous distances involved. Even if the scientists of the future could design spaceships capable of traveling at the speed of light—186,282 miles per second—a return journey to the bright star Aldebaran would take about 136 years. A return journey to Antares would take take about 1040 years. And these distances represent only very tiny fractions of the whole distance of 100,000 light-years across our own Galaxy. A return journey to the nearest other spiral galaxy, the Andromeda Galaxy, would take close to four million years. So unless something quite different and extraordinary is discovered about space or time—something completely outside the realms of present-day science—travel of this kind can never take place.

Even so there is no reason for disappointment. Our knowledge of the universe will certainly extend thousands of millions of light-years farther into space by means of space probes and by sending up space observatories from the Earth. It is here that our real hopes of learning about and exploring the universe lie. And it is this exciting adventure that we have already begun.

Here we see Yuri Gagarin about to enter the Soviet spaceship *Vostok*, which made the first manned orbit of the Earth on April 12, 1961. Since then flights to the Moon and the nearer planets seem real possibilities.

On June 29, 1961, American scientists and technicians made the first launching of a three-in-one satellite. Transit IV-A, the largest of the three, established that the Earth's equator is not round but slightly elliptical.



While the American Mariner II (page 130) was near Venus the Soviet Mars i (below) set off on a probe toward Mars. As rockets, spaceships, and the equipment of satellites improve, our knowledge of the universe will go on growing.

The Planets of the Solar System

	Average distance from Sun in millions of miles	Angle of equator to orbit	Time taken for 1 orbit	Period of Rotation	Equatorial Diameter (miles)	Mass (Earth = 1)
MERCURY	36·0	23° 7′?	88 days	88 days	3,100	0·06
VENUS	67·2	32°?	224¾ days	?	7,700	0·82
EARTH	92·9	23° 27′	365¼ days	23h 56m	7,927	1
MARS	141·5	24°	687 days	24h 37m	4,200	0·11
JUPITER	483·4	3° 4′	11·86 yrs	9h 51m	88,700	318·0
SATURN	886·1	26° 44′	29·46 yrs	10h 14m	75,100	95·2
URANUS	1782	98°	84·01 yrs	10h 49m	29,200	14·6
NEPTUNE	2792	28° 48′	164·79 yrs	14h 0m?	27,700	17·3
PLUTO	3664	?	247·7 yrs	6d 9h?	8,700?	0·9?

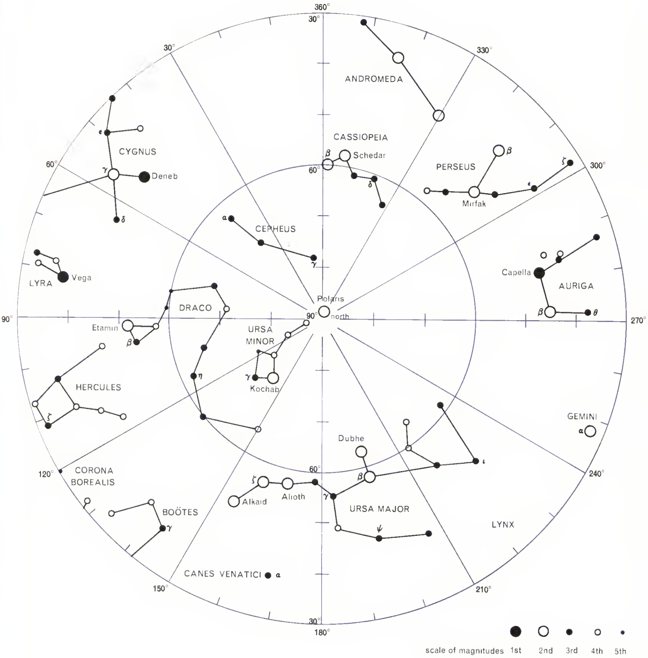
The Satellites of the Planets

	Average distance from center of planet (thousands of miles)	Period of Revolution (days)	Diameter (miles)*
MERCURY			
no satellites			
VENUS			
no satellites			
EARTH			
Moon	239	27·32	2,160
MARS			
Phobos	5·8	0·32	10?
Deimos	14·6	1·26	5?
JUPITER			
V Amalthea	112	0·50	100
I Io	262	1·77	2,020
II Europa	417	3·55	1,790
III Ganymede	665	7·15	3,120
IV Callisto	1,171	16·69	2,770
VI	7,133	250·57	50?
VII	7,295	259·65	20?
X	7,369	263·55	under 10
XII	13,200	631·1	under 10
XI	14,000	692·5	under 10
VIII	14,600	738·9	under 10
IX	14,700	758	under 10
SATURN			
Mimas	116	0·94	300
Enceladus	148	1·37	400
Tethys	183	1·89	600
Dione	235	2·74	600
Rhea	327	4·51	810
Titan	759	15·94	2,980
Hyperion	920	21·28	(100)
Iapetus	2,213	79·33	(500)
Phoebe	8,053	550·45	(100)
URANUS			
Miranda	77	1·41	(200)
Ariel	119	2·52	(500)
Umbriel	166	4·14	300
Titania	272	8·71	600
Oberon	365	13·46	500
NEPTUNE			
Triton	220	5·88	2,300
Nereid	3,461	359·4	200?
PLUTO			
no known satellites			

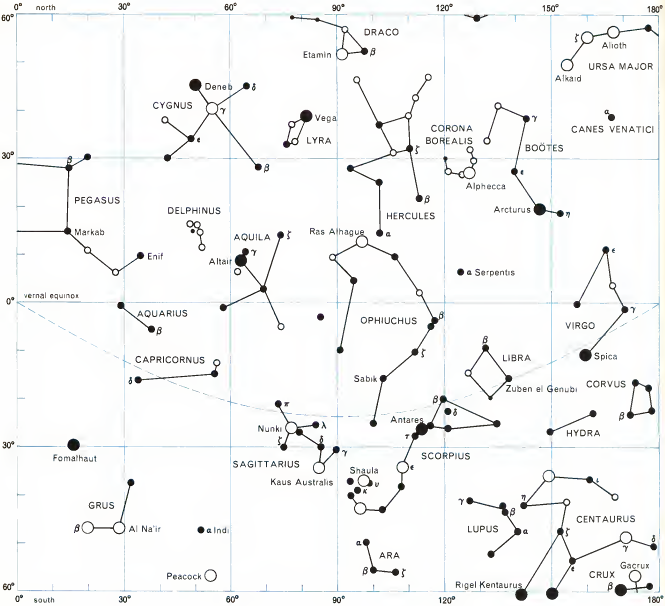
* Figures, especially those in brackets, are approximate, since diameters of satellites are hard to measure precisely.

The Twenty Brightest Stars

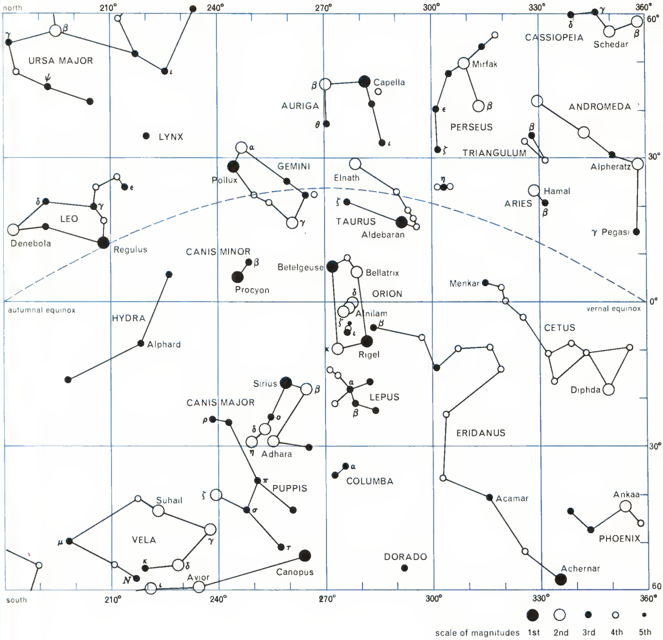
STAR Constellation	Apparent Magnitude	Color
SIRIUS Canis Major	—1·43	White
CANOPUS Carina	—0·73	Yellowish
α CENTAURI Centaurus	—0·27	Yellowish
ARCTURUS Boötes	—0·06	Orange
VEGA Lyra	0·04	Bluish-White
CAPELLA Auriga	0·09	Yellowish
RIGEL Orion	0·15	Bluish-White
PROCYON Canis Minor	0·37	Yellowish
ACHERNAR Eridanus	0·53	Bluish-White
BETELGEUSE Orion	variable	Reddish
β CENTAURI Centaurus	0·66	Bluish-White
ALTAIR Aquila	0·80	White
ALDEBARAN Taurus	0·85	Orange
ACRUX Crux	0·87	Bluish-White
ANTARES Scorpio	0·98	Reddish
SPICA Virgo	1·00	Bluish-White
FOMALHAUT Piscis Australis	1·16	White
POLLUX Gemini	1·16	Orange
DENEB Cygnus	1·26	White
β CRUCIS Crux	1·31	Bluish-White



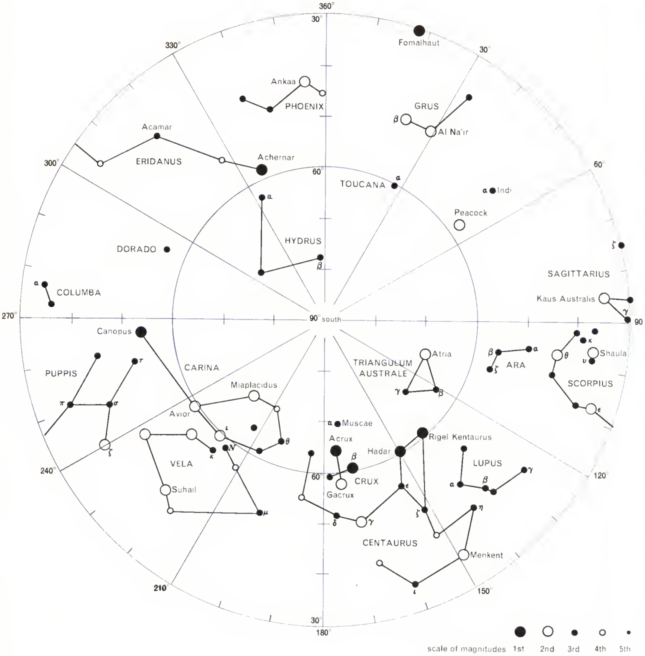
Maps drawn on a flat page must show some distortion of the curved dome of the sky. Here we see the stars around the north celestial pole. Those in the inner circle extend to 60° north (30° from the pole), those in the outer circle to 30° north (60° from the pole). If we had a third circle reaching as far as the celestial equator (90° from the pole) constellations in it would be badly distorted.



This map shows stars within 60° north and 60° south of the celestial equator. If we extended it farther north and south the distortion would again become very pronounced. The curved line shows the ecliptic—the Sun's apparent path among the fixed stars.



north
210°
240°
270°
300°
330°
360°
60°
URSA MAJOR
LYNX
AURIGA
Capella
CASSIOPEIA
Schedar
Mirfak
PERSEUS
ANDROMEDA
TRIANGULUM
30°
Alpheratz
Pollux
GEMINI
Elnath
Hamal
ARIES
LEO
Denebola
Regulus
TAURUS
Aldebaran
γ Pegasi
CANIS MINOR
Procyon
Betelgeuse
Bellatrix
ORION
Menkar
0°
autumnal equinox
vernal equinox
HYDRA
Alnilam
Alphard
Rigel
CETUS
Diphda
Sirius
CANIS MAJOR
LEPUS
ERIDANUS
Adhara
COLUMBA
PUPPIS
Suhail
Acamar
Ankaa
VELA
PHOENIX
DORADO
Canopus
Avior
Achernar
south
scale of magnitudes
1st
2nd
3rd
4th
5th



Here we see the stars around the south pole. The outermost are 30° south of the celestial equator, or 60° from the pole.

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(T) top, (C) center, (B) bottom, and combinations; for example (TL) top left, or (CR) center right

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Gordon Cramp 109(BL)

PLANISPHÆRII COELESTIS HE

Calculatum *ad finem* Anni MDCC *pro* Ævo XVIII praesente:

Cum Privilegio Potentissimorum

Motus Longitudinis Stellarum Fixarum, *secundum* Tychonem.

Menses	Secunda	Anni	Gradus	Minuta	Secunda	Anni	Gradus	Minuta	Secunda
Ianuarius	4	1	0	0	52	13	0	11	3
Februarius	8	2	0	1	42	14	0	11	54
Martius	13	3	0	2	33	15	0	12	45
Aprilis	17	4	0	3	24	20	0	17	0
Majus	21	5	0	4	15	30	0	25	30
Iunius	25	6	0	5	6	40	0	34	0
Iulius	30	7	0	5	57	50	0	42	30
Augustus	34	8	0	6	48	60	0	51	0
September	38	9	0	7	39	70	0	59	30
October	42	10	0	8	30	80	1	8	0
November	47	11	0	9	21	90	1	16	30
December	51	12	0	10	12	100	1	25	0

Planetarum a Terra *Distantiæ Triplices*

Per Semidiametros Terræ dimensæ

1. Lunæ	2. Mercurii	3. Veneris	4. Solis	5. Martis	6. Iovis	7. Saturni
Maxima ... 61	Ma ... 33000	Ma ... 38000	Ma ... 22374	Ma ... 39000	Ma ... 143000	Ma ... 244000
Mediocris ... 57	Me ... 22000	Me ... 22000	Me ... 22000	Me ... 22500	Me ... 115000	Me ... 210000
Minima ... 53	Mi ... 11000	Mi ... 6000	Mi ... 21626	Mi ... 6000	Mi ... 87000	Mi ... 176000

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Menses	Secunda		Anni	Gradus	Minuta	Secunda	Anni	Gradus	Minuta	Secunda
Ianuarius	4		1	0	0	50	13	0	10	50
Februarius	8		2	0	1	40	24	0	11	40
Martius	13		3	0	2	30	15	0	12	30
Aprilis	17		4	0	3	20	20	0	16	40
Majus	21		5	0	4	10	30	0	25	0
Iunius	25		6	0	5	0	40	0	33	20
Iulius	30		7	0	5	50	50	0	41	40
Augustus	34		8	0	6	40	60	0	50	0
September	38		9	0	7	30	70	0	58	20
October	42		10	0	8	20	80	1	6	40
November	47		11	0	9	10	90	1	15	0
December	51		12	0	10	0	100	1	25	20

Planetarum Magnitudines, ratione Terræ.

1 Luna 52.^{um} Terræ partem magnitudine complectitur 2 Mercurius 19000.^{mam} 3 Venus 28.^{vam} aut aliis 37.^{mam} 4 Sol 166.^{ies} Terrâ major habetur. aliis 162 quibusdam tantum 140.^{ies} 5 Mars ratione Terræ est ut 27 ratione 125 6 Iupiter 81. aliisq. 95 Terræ Magnitudines complectitur 7 Saturnus deniq. 79. et quibusdam 91 partibus Terram superat.

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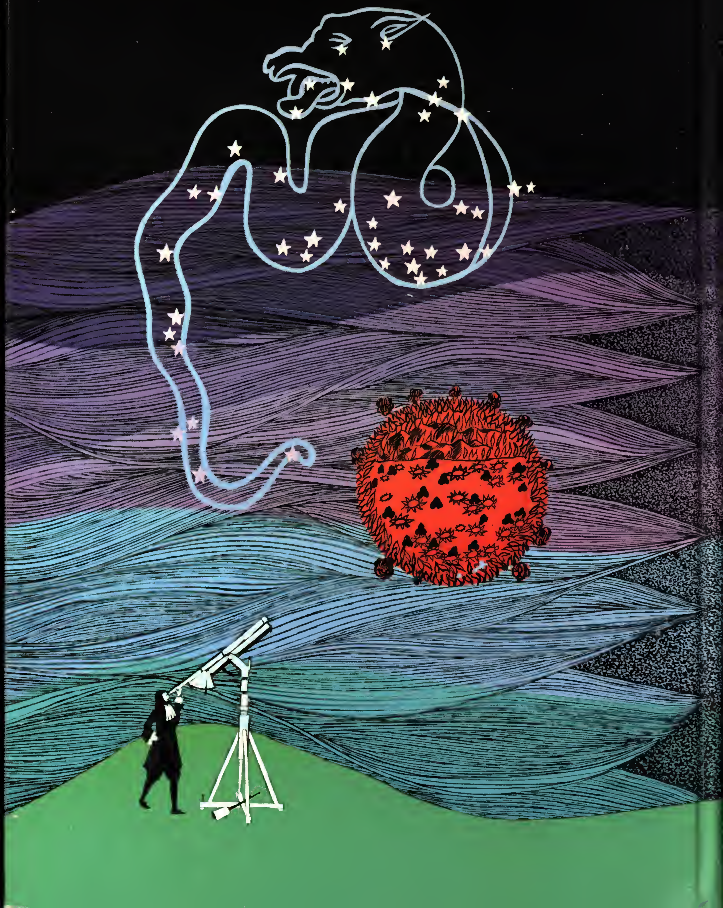

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